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RELIABILITY PREDICTION PROGRAM FOR ORGANIC
RANKINE-CYCLE ENGINE GENERATOR SYSTEMS

by
D.J. Hoffmann

November 1970

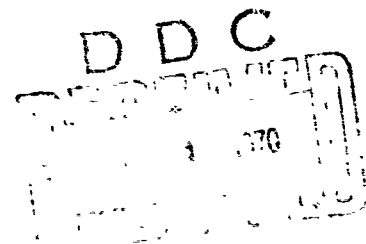
Prepared for
U.S. Army Mobility Equipment
Research and Development Center
under Contract DAAK01-70-D-4142-0002

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ABSTRACT

A reliability-prediction program was conducted by ARINC Research Corporation to provide the U.S. Army Mobility Equipment Research and Development Center with quantitative reliability predictions of two manufacturers' organic Rankine-cycle engine generator systems and a computer program for calculating the predictions. Historical failure data were compiled, and a reliability-prediction mathematical model was developed. A computer program was developed, and reliability predictions were made for the two systems for a variety of missions and environments.

FOREWORD

This report was prepared by ARINC Research Corporation for the U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia, under Contract DAAK01-70-D-4142. Its purpose is to provide a quantitative reliability assessment of engine generator systems currently being developed by Fairchild Hiller, Stratos Division and Thermo Electron Corporation.

SUMMARY

INTRODUCTION

This report presents the results of a reliability-prediction program for closed organic Rankine-cycle engine generator sets. The program was conducted by ARINC Research Corporation for the U.S. Army Mobility Equipment Research and Development Center during the period July 1970 to September 1970.

The Rankine-cycle generator systems of two manufacturers — Fairchild Hiller, Stratton Division, and Thermo Electron Corporation — are considered in this report. Each is a self-contained integrally started power-generator system capable of 24-hour operation on its own fuel supply.

RELIABILITY-PREDICTION MODEL

In preparation for developing the prediction model, parameters that define the systems were specified, together with the missions and environments. The reliability block diagrams and prediction equations (mathematical model) were formulated from system functional schematics, drawings, and diagrams.

FAILURE DATA

A number of failure-rate data sources were surveyed and the failure rates for similar components listed. Operational factors required to adjust each failure rate to the environmental modes and manufacturers' estimates were derived. A Failure Mode and Effect Analysis (FMEA) was also performed.

COMPUTER PROGRAM

A computer program depicting the mathematical prediction model was prepared. This program can be exercised for any basic series-constructed system over a wide range of time. The output (reliability predictions) can be obtained for a variety of mission types over four operating environments. The program was made sufficiently flexible to allow system-configuration changes, as well as failure-rate distributions other than the assumed constant failure rate.

FLUIDIC-CONTROL APPLICATION

The feasibility of utilizing fluidic control devices was investigated briefly. The advantages and disadvantages of such devices, their estimated reliability, and areas of application were evaluated.

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CHAPTER ONE

INTRODUCTION

Under Contract DAAK01-70-D-4142 to the U.S. Army Mobility Equipment Command, ARINC Research Corporation assessed the relative effectiveness of two organic Rankine-cycle power plants under development for the Electrotechnology Laboratory at the U.S. Army Mobility Equipment Research and Development Center (USAMERDC).

The purpose of the assessment was to make quantitative reliability predictions for the two candidate configurations and to provide USAMERDC with the basic tools for performing future reliability analyses. A hypothetical system with idealized characteristics was used to show the ultimate reliability of the Rankine-cycle power plant. The following tasks were performed:

- Review available information on the Rankine-cycle power plants and establish baseline data
- Identify a representative mission and define system failure
- Perform a Failure Mode and Effect Analysis
- Develop a reliability-prediction model at the major-component level sufficiently flexible to permit configuration changes and the use of various types of failure distributions
- Perform a reliability prediction of the two candidate systems and a hypothetical system
- Develop an estimate of the mean active-repair times for the candidate systems and determine the availability of the systems

This report presents a background discussion and description of the candidate systems, Failure Mode and Effect Analyses for the systems, the prediction model and the predictions themselves, and a discussion of the application of fluidic controls to the Rankine-cycle engine. The conclusions and recommendations resulting from the study are also presented.

CHAPTER TWO

BACKGROUND

The U.S. Army is currently conducting a technical evaluation of silent ground-power systems. The Rankine-cycle engine is one of the candidate prime movers for such a system. Two contracts to develop a Rankine-cycle engine generator set were awarded by the U.S. Army Mobility Equipment Research and Development Center (USAMERDC), Ft. Belvoir, Virginia, to Fairchild Hiller Stratos Division, Bay Shore, New York, and Thermo Electron Corporation, Waltham, Massachusetts.

The closed Rankine cycle for steam or organic working fluids involves the four thermodynamic processes shown in the pressure-volume (PV) and temperature-entropy (TS) diagrams of Figure 1.

Ideally, the working fluid undergoes an isothermal and isentropic pressure increase in the feed pump, process 1-2; and a temperature increase in the boiler at constant pressure, saturating, evaporating, and superheating the fluid, process 2-3. Process 3-4 represents an isentropic pressure decrease in the engine; and process 4-1 is the constant-pressure heat transfer in the condenser, condensing the vapor back to a liquid to re-enter the feed pump.

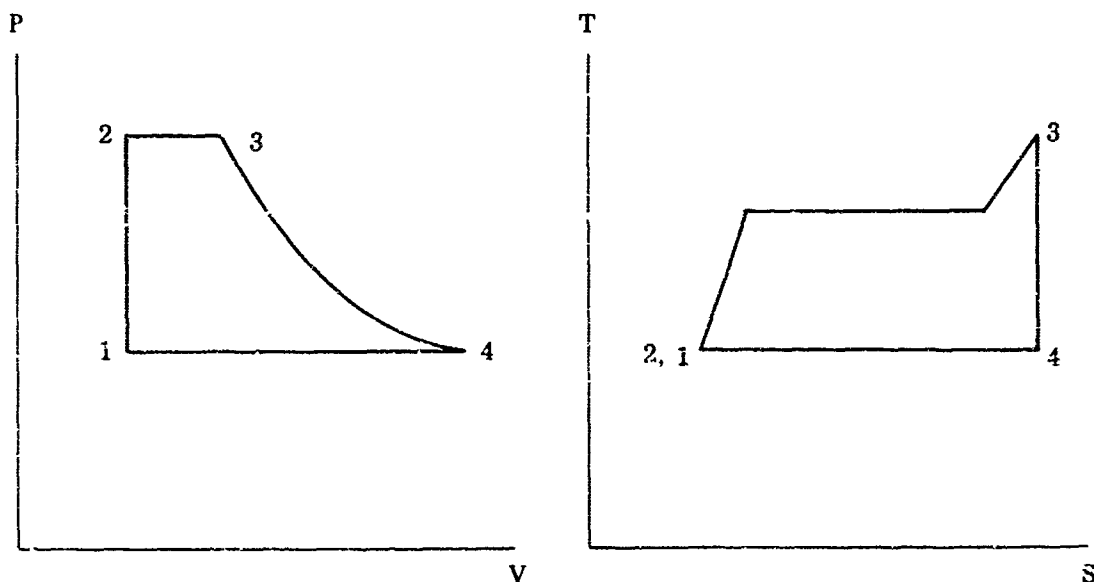


Figure 1. RANKINE CYCLE PV AND TS DIAGRAMS

The organic Rankine-cycle systems have a potential problem area with the organic fluids. If overheated, the fluids undergo thermal decomposition, rendering the system useless.

Figure 2 is a flow schematic for a basic Rankine-cycle engine generator set that uses an organic fluid as the working substance. The numbers correspond to the processes in the cycle. The regenerator is used to increase the efficiency of an organic Rankine cycle. The energy of the superheated exhaust vapor is transferred internally in the cycle to the working fluid after the fluid leaves the feed pump; this significantly reduces the energy required to vaporize or superheat the fluid in the boiler.

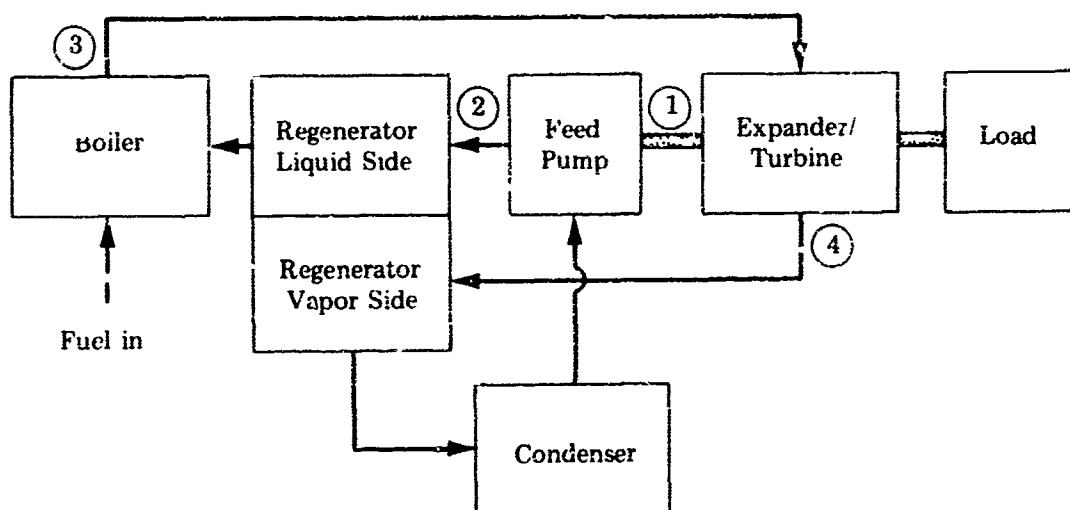


Figure 2. BASIC FLOW SCHEMATIC FOR ORGANIC RANKINE-CYCLE SYSTEM

CHAPTER THREE

RELIABILITY-PREDICTION MODEL

The term "reliability-prediction model" describes the block diagrams and equations that depict and mathematically relate component reliabilities to overall system reliability. The development of a reliability-prediction model encompasses several tasks:

- Definition of the system mission
- Definition of system failure
- Statement of assumptions
- Development of reliability block diagrams
- Development of reliability-prediction equations

3.1 SYSTEM DEFINITIONS

The two manufacturers' systems are similar. The major difference that might affect reliability is in the power output level of the generator sets, which affects set size. The following system descriptions show the differences between the manufacturers' designs.

3.1.1 Fairchild Hiller, Stratos Division System

Fairchild Hiller Stratos Division, hereinafter called STRATOS, is designing a 1.5-kW organic Rankine-cycle engine generator set rated at 28 Vdc. The set will be inaudible at 100 meters, will weigh approximately 150 pounds, and will measure approximately 2' x 2' x 2'.

Figure 3 is a flow schematic of the STRATOS generator set. The organic working fluid is FC75. To protect against overheating or overpressurization, a thermal sensor is placed at the fluid exit point on the boiler to shut the system down. A pressure-burst disc is also placed in the fluid loop for additional protection of the system components in case the thermal sensor fails and the system becomes overpressurized to the point of catastrophic line or component rupture.

The turbo alternator pump is the unique component in the STRATOS generator set. It combines three components into one on a single rotating shaft. The two fluid-film journal bearings and a thrust bearing are lubricated by the working fluid. The unit is hermetically sealed in the fluid loop, two fluid drains in the alternator case remove entrapped FC75. Liquid FC75 flows in a coil around the alternator portion of the turbo alternator pump to cool the windings. The power-conditioning circuits are mounted on a cooling plate for the same purpose. This keeps all of the major power-producing elements at a constant temperature during system operation.

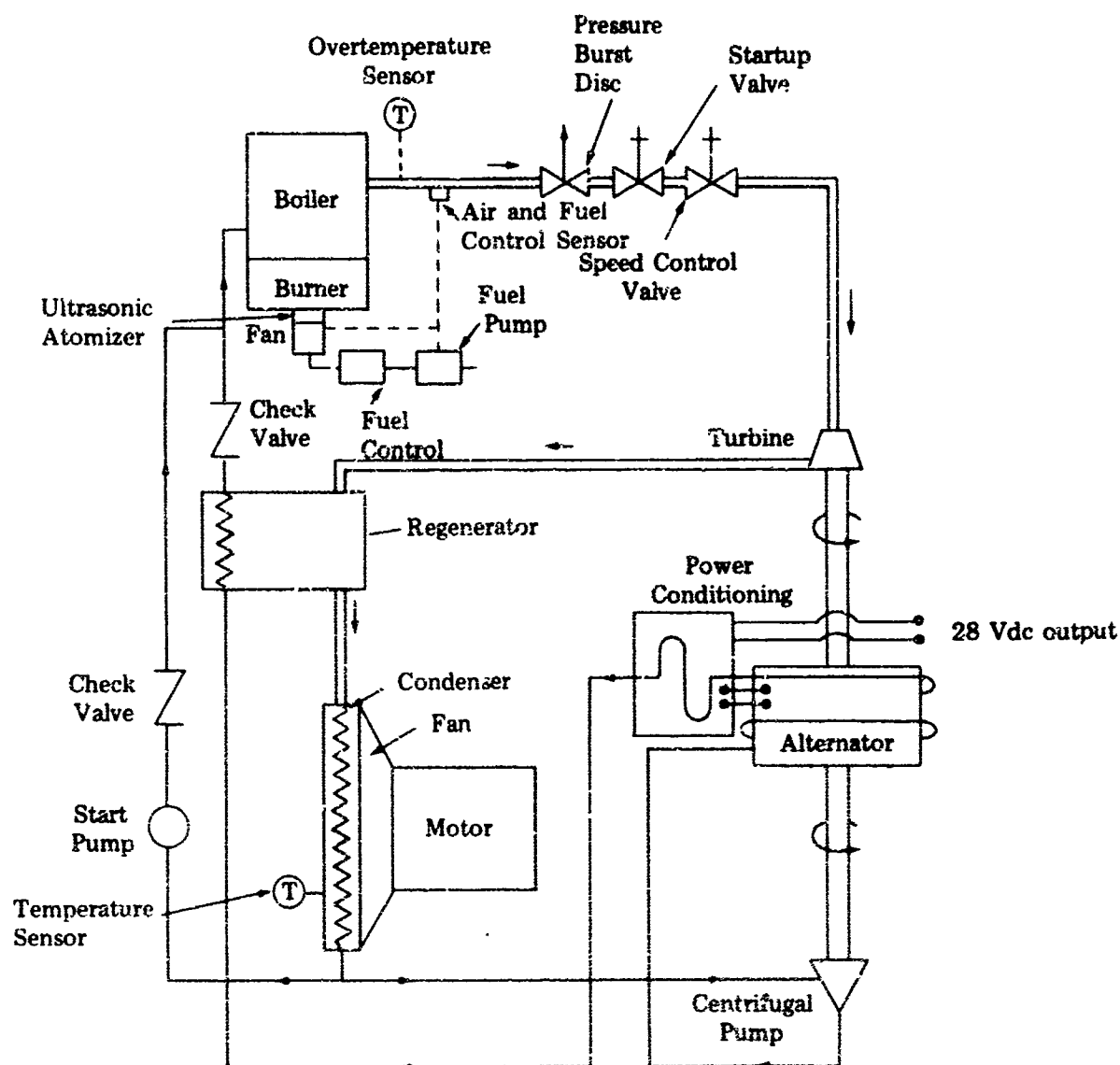


Figure 3. STRATOS ENGINE GENERATOR SET

The condenser fan and the fuel pump are driven by variable-speed motors. The motor speeds are adjusted by thermal sensing circuits to maintain constant fluid-loop conditions.

The alternator speed is kept constant by a solenoid modulation valve in the fluid loop just prior to the turbine inlet. The valve is controlled by a circuit that detects the output of the alternator and sends a signal to the solenoid to vary the flow rate to the turbine. The feed pump is a centrifugal noncavitating pump whose output is kept constant by the alternator's fixed RPM.

The fluid loop is hermetically sealed. It is therefore repairable only at the depot level. Most support components in the systems (see Chapter Two) are repairable at the organizational level of maintenance. The electrical and electronic circuits are currently planned to be field- or depot-repairable.

3.1.2 Thermo Electron Corporation System

Thermo Electron Corporation, hereinafter called TECO, is designing a 3-kW, 120-Vac Rankine-cycle generator set. It will be inaudible at 100 meters, weigh approximately 300 pounds, and measure approximately $2.5' \times 2.5' \times 2.5'$. Figure 4 is a functional schematic of the TECO generator set.

CP34, an organic substance, is used as the working fluid. To protect against overpressure or temperature, safety sensors are placed in the fluid loop. The boiler requires a buffer fluid around the organic fluid because of the extreme temperatures. The buffer fluid transfers the thermal energy to the working fluid. The flow energy of the vapor is converted to rotary motion in a reciprocating two-cylinder engine that is coupled to the alternator. The vapor is then exhausted through the regenerator to the condenser. A positive-displacement piston feed pump is gear-driven off the engine; it is located upside-down to form the bottom of the engine crankcase. The crankcase is filled with a silicone lubricant to lubricate both the engine and the feed pump. The silicone is miscible with the CP34; a fluid/lubricant separator is thus necessary in the loop since the seals and rings in the engine and feed pump are not 100-percent leakproof.

When the system is not in use, the working fluid and lubricant characteristically migrate to the engine crankcase. A starting fluid reservoir is placed in the loop to drain the accumulated fluid from the engine. This reservoir provides the fluid to the start pump, preventing pump cavitation at system startup.

A motor-driven throttle valve is used to maintain constant engine speed. Alternator output is sensed by a speed-control circuit, and a control signal is sent to the valve's driving motor.

The fluid loop is hermetically sealed, except for the shaft seal on the engine crankshaft which must penetrate the crankcase to connect to the alternator, making it extremely impractical for the user or field-support maintenance facilities to repair components in the loop. Most of the electrical and electronic components, fuel- and air-supply components, and condenser fan are planned to be field-repairable.

3.2 SYSTEM MISSIONS

The U.S. Army Mobility Equipment Research and Development Center has established a goal of a 95-percent reliability for the generator sets, with a confidence level of 90

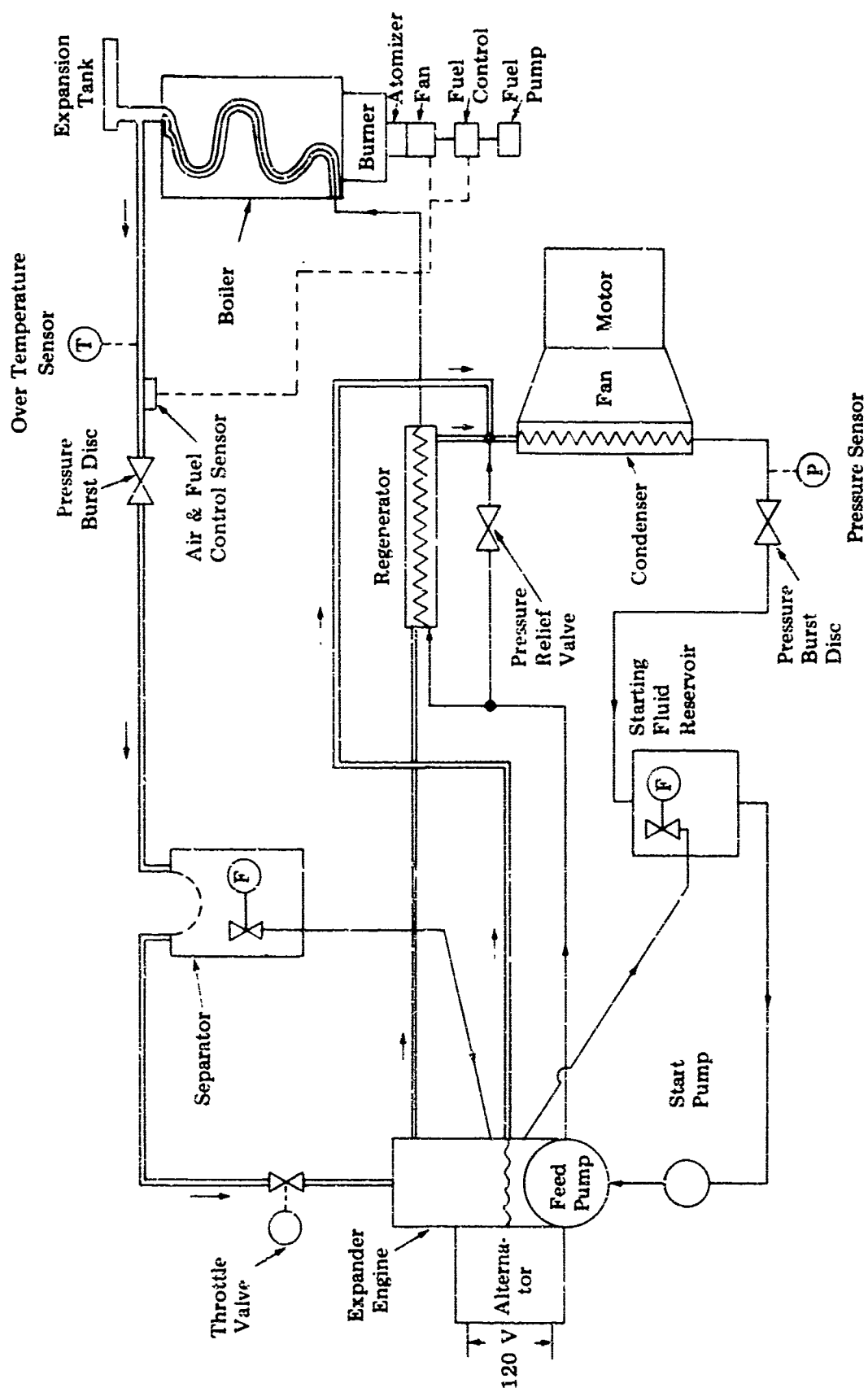


Figure 4. TECO ENGINE GENERATOR SET

percent, for a mission duration of 24 hours and an inherent availability of 98 percent. ARINC Research Corporation used this requirement as a basis for developing two representative missions.

3.2.1 Mission Profile

3.2.1.1 Mission I

The first mission is for the Rankine-cycle generator set to start up in three minutes (0.05 hour) and continuously deliver power for 24 hours without shutting down. It is connected to an external fuel tank, but this fuel source is not considered in the reliability model.

3.2.1.2 Mission II

The second mission involves cycling the generator set through startup and power delivery four times in 100 hours. Two of the startups are hard starts, requiring six minutes (0.1 hour) each; the other two starts require the normal three minutes. The sets deliver power continuously for 25 hours after each start.

3.2.2 Environments

At the beginning of the project it was planned to incorporate the effects of temperature and weather conditions as the environmental effects on the system. It became apparent, however, that there was little operational information on mechanical and electromechanical equipment that reflected these environmental factors. Data were available on several operating applications for these equipments; the three of these which were used are described below.

3.2.2.1 Portable Ground Environment

The generator set is in a portable condition, not rigidly mounted in a fixed installation; it can be moved from place to place in vehicles traveling over unimproved roads and can be loaded and unloaded manually.

3.2.2.2 Tracked-Vehicle Environment

The generator set is mounted on a tracked vehicle capable of traveling over open terrain. The set is subject to severe shock and vibration in transport. The sets will normally be operated while the vehicle is not moving, although operation is not restricted to times when the vehicle is stationary.

3.2.2.3 Laboratory Environment (Hypothetical System With Idealized Characteristics)

The laboratory environment was used to meet the contract requirement to develop a prediction for a hypothetical system with idealized characteristics. The laboratory conditions are based on the assumption that the sets are functioning in an ideal environment with skilled personnel performing the operational tests. It is believed that the data produced under these conditions show the best achievable reliability for the prototype models and indicate what can be expected from production units in the field that are superior in design and reliability to the prototype generator sets. The system manufacturers currently believe that the best method to achieve higher system reliability is to improve the design rather than incorporate redundancy.

3.3 FAILURE DEFINITIONS

The loss of any critical component that prevents the generator system from meeting 100-percent power-output capability results in system failure. A critical component is any item or part whose failure would preclude successful operation of the system or create safety hazards. Included in this category are the components required for starting the system since without starting capability power output cannot be achieved.

Failure of any safety-shutdown circuit is a system failure. These circuits are fail-safe -- that is, the loss of one of them will automatically shut down the system.

3.4 ASSUMPTIONS

After the systems, the missions, and failure were defined, the following major assumptions were made to establish prediction-model limitations:

- Once the system has exceeded the infant-mortality period, the failure rate does not change during the life of the system (exponential distribution).
- All components must function properly at the prescribed time in the mission for complete system success.
- System safety-shutdown circuits are not fail-safe.
- Generator-set maintenance will not include any components in the fluid loop, because the loop is hermetically sealed by the manufacturer or depot.

3.5 RELIABILITY BLOCK DIAGRAMS

A reliability block diagram is a pictorial chart of a system or subsystem that depicts the interactions between the components of the system and the effects of a component failure on the system.

Figure 5 is the reliability block diagram for an organic Rankine-cycle engine generator system composed of four functional groups or subsystems:

- **Fluid-Loop Group** -- any component that comes into direct active contact with the organic fluid
- **Power-Generation Group** -- the components and circuits that make up the power-generation, -conditioning, and -rectifying segment of the generator sets (excluding the alternator in the STRATOS system, which is included in the fluid-loop group because it is hermetically sealed in the loop)
- **Electronic Control Circuits Group** -- the circuits that control, regulate, and protect the generator set, along with the electronic or electrical sensors providing the proper input signals
- **Support-Components Group** -- components or items that do not directly fall into the other three groups and provide a supporting service to the end mission of the generator set

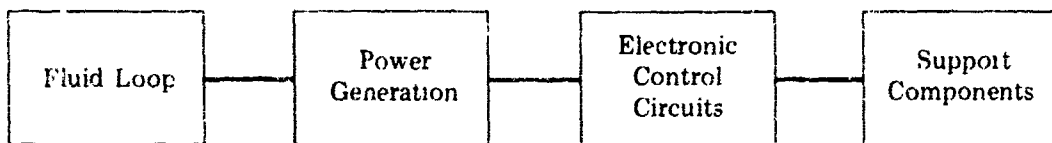


Figure 5 RELIABILITY BLOCK DIAGRAM, ORGANIC RANKINE-CYCLE ENGINE GENERATOR SYSTEM

Figures 6 and 7 are the functional-group reliability block diagrams for the STRATOS and TECO systems, respectively. A five-digit code is assigned to every block in the reliability diagrams for identification in the computer mathematical model when failure distributions are being inputted. Whenever a change is made in the diagram, it is necessary to add or subtract a code depending on whether a component is added or removed.

3.6 RELIABILITY-PREDICTION EQUATION

The reliability-prediction equation expresses the mathematical relationships between the system components in the reliability block diagram, showing how they are related to overall system reliability.

The Rankine-system components have basically a direct series relationship. The computer model calculates the reliabilities of all the components individually. The failure distribution of each component or circuit, the amount of accrued operating time on the component, and whether or not the component is a redundant element in the overall model are required for these calculations. These data are inputted into the model with the component's five-digit identification number (see Chapter Six).

The series model for either generator system composed of n elements can be simply expressed as

$$R_s = \prod_{i=1}^n R_i(t) = R_1 \cdot R_2 \cdot R_3 \cdots R_n$$

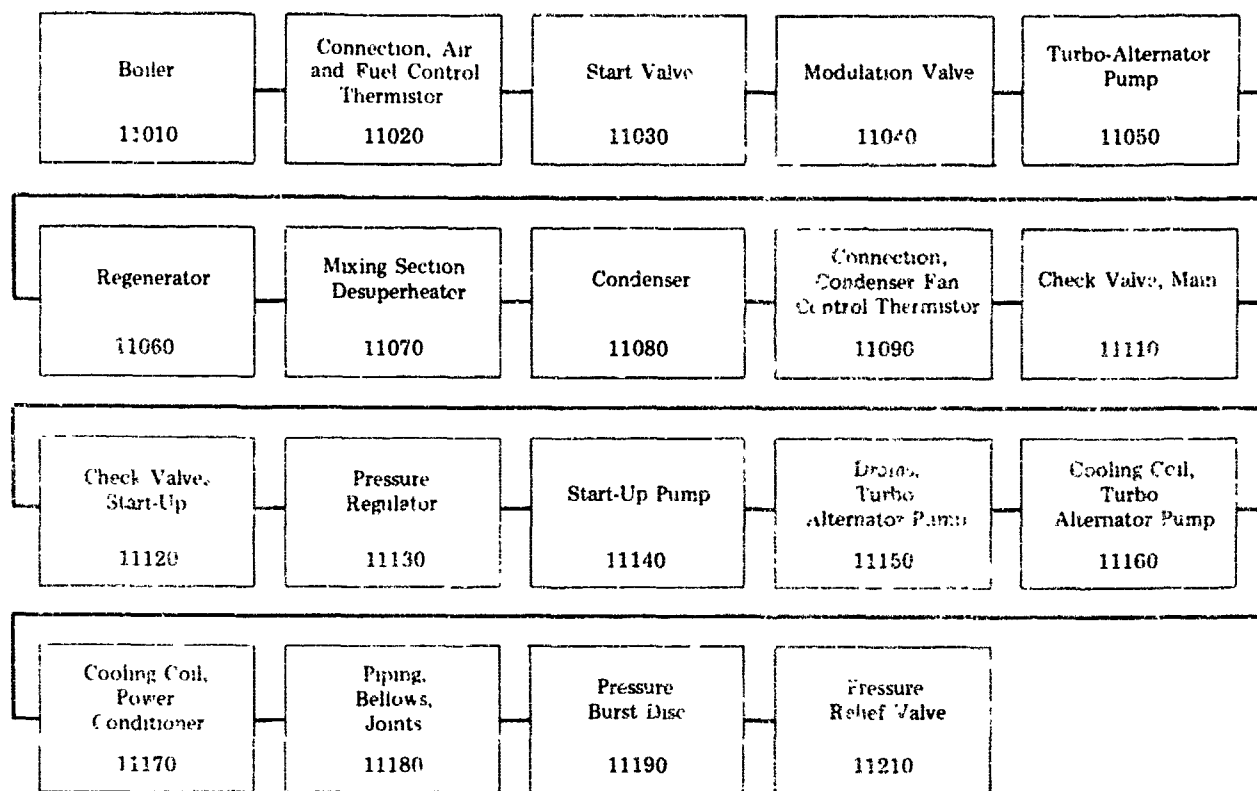
The equations for calculating the reliabilities from the four distributions used in this study for any single component are as follows:

Exponential

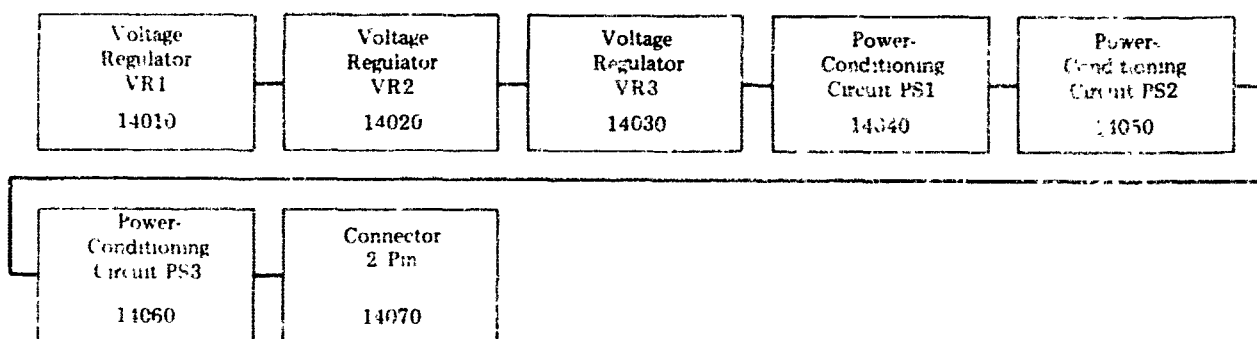
$$R_i(t) = e^{-\lambda_i t}$$

Normal

$$R_i(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\theta)^2}{2\sigma^2}} dt$$

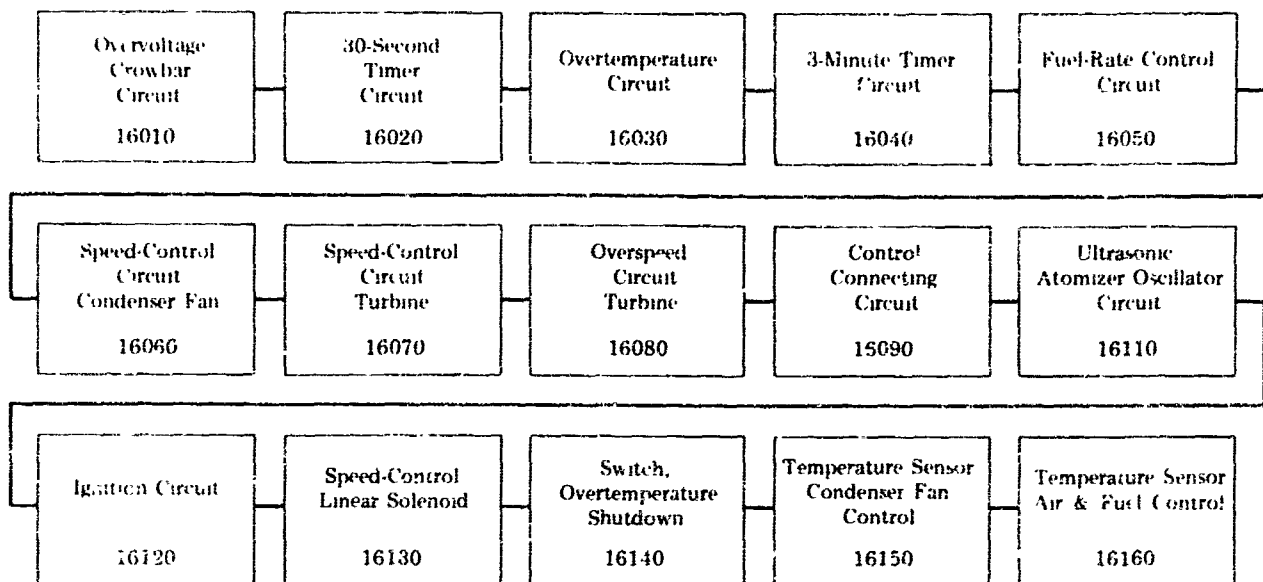


(a) Fluid Loop, 11000

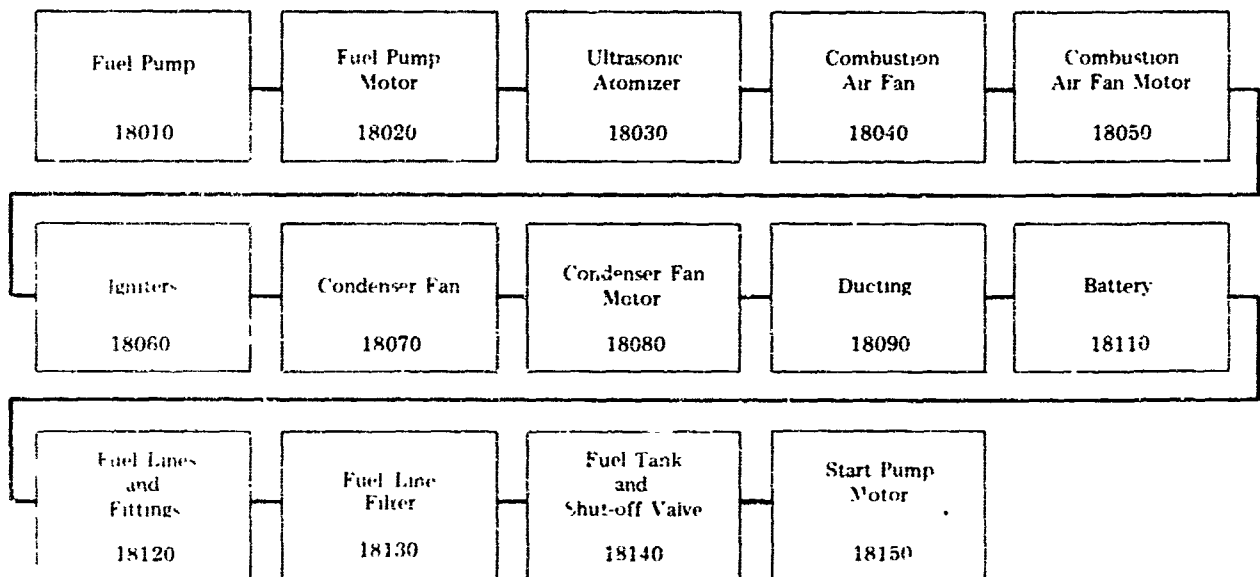


(b) Power Generation, 14000

Figure 6 FUNCTIONAL-GROUP RELIABILITY BLOCK DIAGRAMS FOR STRATOS SYSTEM

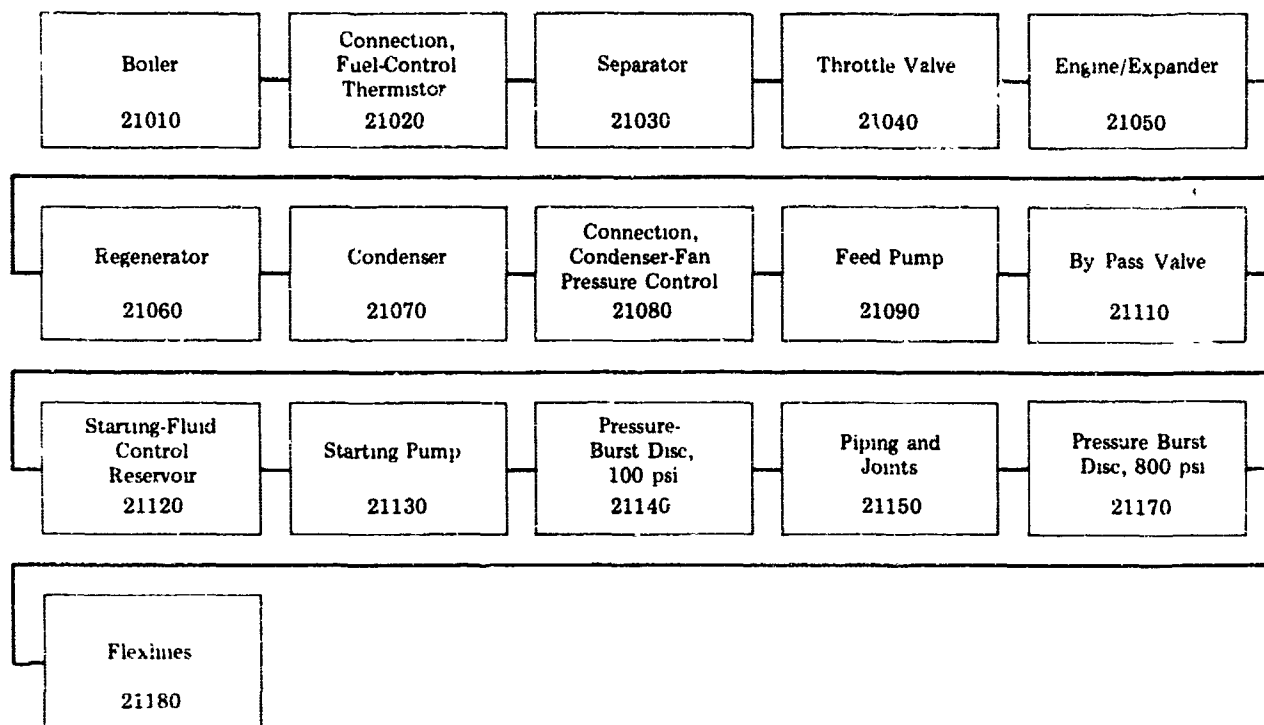


(c) Electronic Control Circuits, 16000

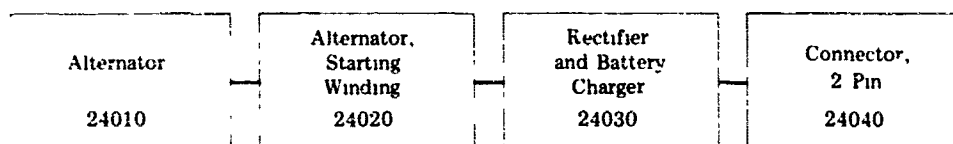


(d) Support Components, 18000

Figure 6 (continued)

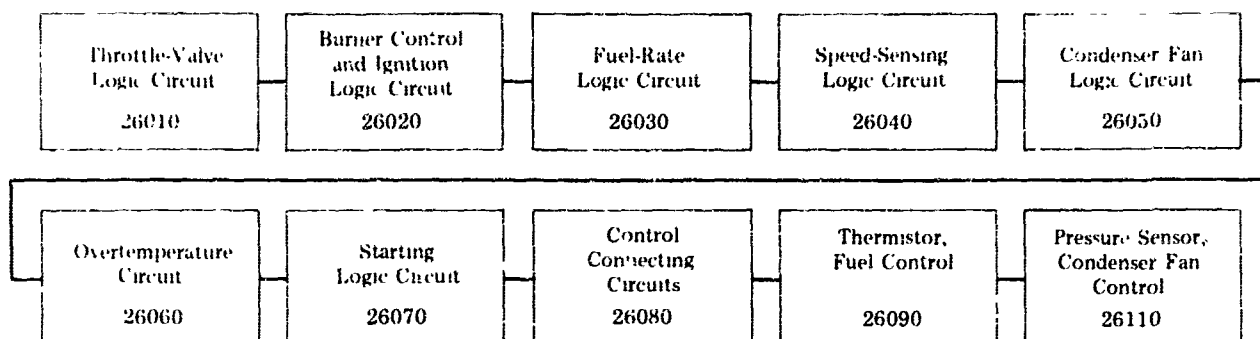


(a) Fluid Loop, 21000

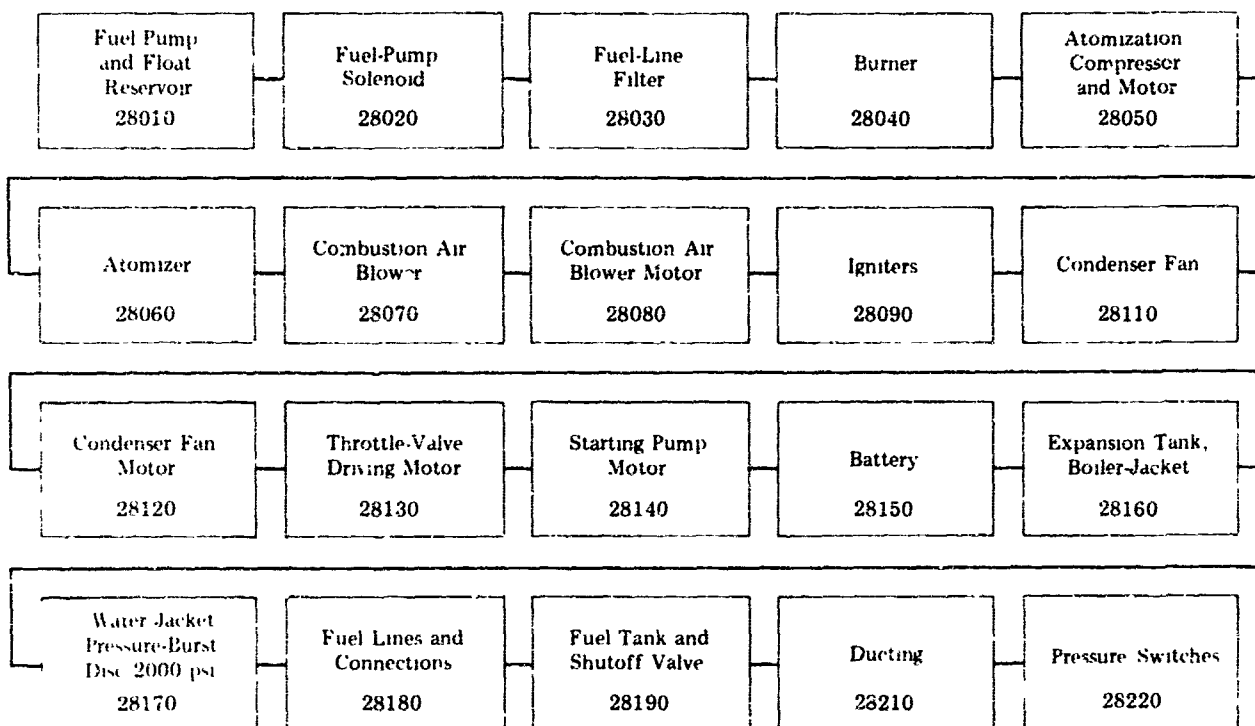


(b) Power Generation, 24000

Figure 7. FUNCTIONAL-GROUP RELIABILITY BLOCK DIAGRAMS FOR TECO SYSTEM



(c) Electronic Control Circuits, 26000



(d) Support Components, 28000

Figure 7 (continued)

Log Normal

$$R_i(t) = \int_t^{\infty} \frac{1}{\sigma \sqrt{2\pi}} \frac{1}{t} e^{-\frac{(\ln \theta t)^2}{2\sigma^2}} dt$$

Probability

$R_i(t)$ = Probability of success

It was necessary to use exponential data for the predictions. However, during prototype testing and development testing, with the proper data-collection techniques and sufficient test time, it will be possible to develop the true failure distributions for each component.

CHAPTER FOUR

DATA COLLECTION

4.1 DEVELOPMENT OF EQUIPMENT FAILURE RATES

Since operational data were not available for most of the components in the two systems, it was necessary to research a number of failure-data sources to obtain data on similar components. The primary sources are Government and contractor data banks, which offer failure histories for a variety of mechanical, electrical, and electronic components. The sources used for this study are listed in Appendix A.

To obtain appropriate component failure rates, all the available failure rates from the data sources used were listed and then screened for a best-fit average failure rate in a known environmental condition. The environmental conditions for the data ranged from the laboratory to space vehicles. Tables 1 and 2 present component failure rates for the two Rankine-cycle generator systems. It is emphasized that all of the failure rates are exponentially distributed.

It was assumed that a portable generator set would not be subject to a single environment; therefore, three K factors were developed from the data sources. The fourth K factor is not environmentally oriented but simply adjusts the failure rate listed in the table to that developed by the manufacture. It is thus possible to show the manufacturers' estimated reliability in comparison with the three environmental categories described in Chapter Three. The K factors are as follows:

- K₁ -- Manufacturer Adjusting Factor
- K₂ -- Portable-Ground-Environment Factor
- K₃ -- Track-Vehicle-Mounted Factor
- K₄ -- Laboratory (Hypothetical System) Factor

It is apparent from the tables that there are numerous adjusting K factors for each environmental condition. The reason for this is that different data sources were used and there is no universal factor for all equipments. The failure rates of most equipments increase as shock and vibration increase; thus a higher multiplying K factor is required for the tracked-vehicle environment to increase the average failure rate.

There are very few failure data on mechanical equipments that show the effects of extreme cold or heat on operating life. Temperature effects were therefore not considered in the environmental conditions.

The delivery of the manufacturer's prototype system to USAMERDC for operational testing is the ideal time to begin a data-collection program. There is very little operational information on organic Rankine-cycle systems; to perform a complete evaluation of the

Table 1. COMPONENT FAILURE DATA, STRATOS ENGINE GENERATOR SET

| Group Block Number | Component Name | Failures Per Million Hours | K ₁ | K ₂ | K ₃ | K ₄ | Data Source |
|--------------------|---|----------------------------|----------------|----------------|----------------|----------------|-------------|
| 11010 | Heater, Boiler | 4.0 | 5.63 | 10.0 | 25.0 | 1.0 | 2 |
| 11020 | Connection, Thermistor, Fuel Control | 0.03 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11030 | Start Valve | 6.88 | 1.89 | 10.0 | 25.0 | 1.0 | 2 |
| 11040 | Modulation Valve | 8.5 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11050 | Turbo Alternator Pump | 24.2 | 2.48 | 1.0 | 2.5 | 0.2 | 2 |
| 11060 | Regenerator | 4.2 | 3.81 | 10.0 | 25.0 | 1.0 | 2 |
| 11070 | Mixing-Section Desuperheater | 4.6 | 9.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11080 | Condenser | 5.33 | 3.57 | 10.0 | 25.0 | 1.0 | 1 |
| 11090 | Connection, Thermistor, Condenser Fan Control | 0.03 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11110 | Check Valve, Main | 5.0 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11120 | Check Valve, Startup | 5.0 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11130 | Pressure Regulator | 2.14 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11140 | Start Pump | 3.1 | 1.325 | 1.0 | 2.5 | 0.2 | 1 |
| 11150 | Drains, Turbo Alternator, Pump (2) | 0.03 | 0.0 | 1.0 | 2.5 | 0.2 | 2 |
| 11160 | Cooling Coil, Turbo Alternator Pump | 1.65 | 0.0 | 1.0 | 2.5 | 0.2 | 1 |
| 11170 | Cooling Plate, Power Conditioning | 1.65 | 0.0 | 1.0 | 2.5 | 0.2 | 1 |
| 11180 | Lines and Fittings (40) | 2.0 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 11190 | Pressure-Burst Disk | 0.6 | 0.0 | 1.0 | 1.5 | 0.2 | 1 |
| 11210 | Pressure Relief Valve | 17.7 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 14010 | Voltage Regulator 1 | 32.805 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 14020 | Voltage Regulator 2 | 29.878 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 14030 | Voltage Regulator 3 | 3.507 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 14040 | Power-Conditioning Circuit 1 | 11.283 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 14050 | Power-Conditioning Circuit 2 | 0.2 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 14060 | Power-Conditioning Circuit 3 | 0.075 | 1.0 | 2.0 | 10.0 | 0.1 | 5 |
| 16070 | Connector, 2 Pin (Female) | 0.1 | 1.0 | 1.1 | 5.0 | 0.1 | 4 |
| 16010 | Overvoltage Crowbar Circuit | 2.0 | 1.0 | 1.0 | 6.0 | 0.25 | 4 |
| 16020 | 30-Second Timer Circuit | 14.3 | 0.175 | 1.0 | 7.75 | 0.175 | 4 |
| 16030 | Overtemperature Circuit | 14.3 | 0.14 | 1.0 | 7.75 | 0.145 | 4 |
| 16040 | 3 Minute Timer Circuit | 50.0 | 0.3 | 1.0 | 5.0 | 0.3 | 4 |
| 16050 | Fuel Rate Control Circuit | 83.3 | 0.24 | 1.0 | 7.5 | 0.24 | 4 |
| 16060 | Speed Control Circuit, Condenser Fan | 83.3 | 0.24 | 1.0 | 7.5 | 0.24 | 4 |
| 16070 | Speed Control Circuit, Turbine | 83.3 | 0.24 | 1.0 | 7.5 | 0.24 | 4 |
| 16080 | Overspeed Circuit, Turbine | 83.3 | 0.24 | 1.9 | 7.5 | 0.24 | 4 |
| 16090 | Control Connecting Circuit | 25.0 | 0.94 | 1.0 | 6.67 | 0.25 | 4 |
| 16110 | Ultrasonic Oscillator Circuit | 50.0 | 0.3 | 1.0 | 5.0 | 0.3 | 4 |
| 16120 | Ignition Circuit | 25.0 | 0.52 | 1.0 | 6.67 | 0.52 | 4 |
| 16130 | Speed Control Linear Solenoid | 6.0 | 1.0 | 1.0 | 1.5 | 0.21 | 4 |
| 16140 | Switch, Overtemperature Shutdown | 2.10 | 2.48 | 1.0 | 2.5 | 0.1 | 3 |
| 16150 | Temperature Sensor, Fuel Control | 6.0 | 0.83 | 1.0 | 2.5 | 0.2 | 3 |
| 16160 | Temperature Sensor, Condenser Fan Control | 0.3 | 0.0 | 10.0 | 25.0 | 1.0 | 3 |
| 18010 | Fuel Pump | 4.94 | 1.72 | 1.0 | 2.5 | 0.23 | 1 |
| 18020 | Fuel Pump Motor | 0.3 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 18030 | Atomizer | 40.5 | 2.1 | 1.0 | 1.0 | 0.1 | 1 |
| 18040 | Fan, Air Flow | 3.3 | 2.57 | 1.0 | 1.75 | 0.1 | 2 |
| 18050 | Fan Motor, Air Flow | 0.2 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 18060 | Igniters (2) | 3.62 | 0.0 | 1.0 | 6.0 | 0.05 | 1 |
| 18070 | Fan, Condenser | 6.6 | 2.36 | 1.0 | 2.5 | 0.1 | 1 |
| 18080 | Fan Motor, Condenser | 8.1 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 18090 | Ducting | 12.46 | 0.0 | 1.0 | 2.5 | 0.75 | 1 |
| 18110 | Battery | 8.1 | 0.0 | 1.0 | 2.5 | 0.2 | 1 |
| 18120 | Lines and Fittings, Fuel | 1.2 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 18130 | Fuel Filter | 0.3 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 18140 | Fuel Tank and Shutoff Valve | 10.1 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 18150 | Start Pump Motor | 20.1 | 0.0 | 1.0 | 1.5 | 0.5 | 1 |

n = 55 (total number of components)

DATA SOURCE: (1) FARADA
(2) Mechanical Design and Systems Handbook
(3) Apollo Reliability Prediction, Estimation and Evaluation Guidelines
(4) MIL-HDBK 217A
(5) Manufacturer

Table 2 COMPONENT FAILURE DATA, TECO ENGINE GENERATOR SET

| Group Block Number | Component Name | Failures Per Million Hours | K ₁ | K ₂ | K ₃ | K ₄ | Data Source |
|--------------------|--|----------------------------|----------------|----------------|----------------|----------------|-------------|
| 21010 | Boiler | 4.9 | 1.02 | 8.0 | 22.0 | 1.0 | 3 |
| 21020 | Connection Thermistor, Fuel Control | 0.03 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 21030 | Separator | 1.30 | 3.46 | 8.0 | 22.0 | 1.0 | 1 |
| 21040 | Throttle Valve | 21.3 | 1.65 | 1.0 | 2.0 | 0.83 | 1 |
| 21050 | Engine, Expander | 31.6 | 0.475 | 1.0 | 2.24 | 0.275 | 1 |
| 21060 | Regenerator | 4.20 | 0.595 | 10.0 | 25.0 | 1.0 | 2 |
| 21070 | Condenser | 5.33 | 1.3 | 10.0 | 25.0 | 1.0 | 1 |
| 21080 | Connection, Pressure Sensor, Condenser Fan Control | 0.02 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 21090 | Feed Pump | 36.5 | 0.274 | 1.0 | 1.37 | 0.334 | 1 |
| 21110 | Pressure-Control Valve | 5.92 | 2.04 | 8.0 | 22.0 | 1.0 | 3 |
| 21120 | Starting-Fluid Reservoir | 24.3 | 0.1975 | 1.0 | 2.83 | 0.1 | 1 |
| 21130 | Start Pump | 3.4 | 1.38 | 1.0 | 3.5 | 0.144 | 1 |
| 21140 | Pressure-Burst Disk, 100 psi | 0.6 | 0.833 | 1.0 | 1.5 | 0.2 | 1 |
| 21150 | Lines and Fittings (40) | 2.0 | 5.0 | 10.0 | 25.0 | 1.0 | 2 |
| 21170 | Pressure-Burst Disk, 800 psi | 0.6 | 0.833 | 1.0 | 1.5 | 0.2 | 1 |
| 21180 | Flex Lines | 34.84 | 0.287 | 1.0 | 1.57 | 0.51 | 1 |
| 24010 | Alternator | 0.7 | 2.86 | 8.0 | 22.0 | 1.0 | 3 |
| 24020 | Alternator Starter Winding | 0.3 | 0.0 | 8.0 | 22.0 | 1.0 | 3 |
| 24030 | Rectifier and Battery Charger | 20.2 | 0.5 | 1.0 | 8.66 | 0.6 | 1 |
| 24040 | Connector, 2-pin (Female) | 0.4 | 0.0 | 10.0 | 25.0 | 1.0 | 1 |
| 26010 | Throttle Valve Control Circuit | 83.3 | 0.356 | 1.0 | 7.5 | 0.2 | 4 |
| 26020 | Burner Control and Ignition Logic Circuit | 36.3 | 0.723 | 1.0 | 4.15 | 0.2 | 4 |
| 26030 | Fuel-Rate Circuit | 83.3 | 0.0 | 1.0 | 7.5 | 0.2 | 4 |
| 26040 | Speed-Control Circuit, Alternator | 83.3 | 0.0 | 1.0 | 7.5 | 0.2 | 4 |
| 26050 | Speed-Control Circuit, Condenser Fan | 83.3 | 0.0 | 1.0 | 7.5 | 0.2 | 4 |
| 26060 | Overpressure Shutdown Circuit | 14.3 | 0.0 | 1.0 | 7.75 | 0.2 | 4 |
| 26070 | Starting Logic Circuit | 64.3 | 0.0 | 1 | 5.61 | 0.2 | 4 |
| 26080 | Control Connecting Circuit | 25.0 | 0.0 | 1.0 | 6.68 | 0.2 | 4 |
| 26090 | Thermistor, Fuel Control | 0.6 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 26110 | Pressure Sensor, Condenser Fan Control | 3.5 | 0.0 | 8.0 | 22.0 | 1.0 | 3 |
| 28010 | Fuel Pump and Float Reservoir | 29.23 | 0.676 | 1.0 | 2.5 | 0.2 | 1 |
| 28020 | Fuel Pump Solenoid | 5.38 | 0.0 | 1.0 | 2.5 | 0.2 | 1 |
| 28030 | Fuel-Line Filter | 0.3 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 28040 | Burner | 4.4 | 1.0 | 1.0 | 2.5 | 1.0 | 5 |
| 28050 | Atomization Compressor and Motor | 18.26 | 1.1 | 1.0 | 2.5 | 0.1 | 1 |
| 28060 | Atomizer | 10.1 | 0.0 | 1.0 | 1.0 | 0.1 | 1 |
| 28070 | Combustion Air Blower | 3.3 | 0.91 | 1.0 | 2.5 | 0.1 | 1 |
| 28080 | Motor, Combustion Air Blower | 2.35 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 28090 | Igniters | 3.62 | 0.0 | 1.0 | 6.0 | 0.05 | 1 |
| 28110 | Condenser Fan | 6.6 | 0.757 | 1.0 | 2.5 | 0.1 | 1 |
| 28120 | Motor, Condenser Fan | 4.21 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 28130 | Motor, Throttle Valve Driving | 1.51 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 28140 | Motor, Starting Pump | 29.2 | 0.0 | 1.0 | 1.5 | 0.5 | 1 |
| 28150 | Battery | 8.1 | 0.123 | 1.0 | 2.5 | 0.2 | 1 |
| 28160 | Expansion Tank, Water Jacket | 0.08 | 0.0 | 10.0 | 25.0 | 1.0 | 1 |
| 28170 | Pressure-Burst Disk, 2000 psi | 0.6 | 0.833 | 1.0 | 1.5 | 0.2 | 1 |
| 28180 | Fuel Lines and Connections | 1.2 | 0.0 | 10.0 | 25.0 | 1.0 | 2 |
| 28190 | Fuel Tank and Shutoff Valve | 10.1 | 0.0 | 1.0 | 2.5 | 0.1 | 1 |
| 28210 | Ducting | 12.46 | 0.0 | 1.0 | 2.5 | 0.75 | 1 |
| 28220 | Pressure Switch | 7.87 | 0.172 | 1.0 | 2.5 | 0.1 | 1 |

n = 55 (total number of components)

DATA SOURCE (1) FARADA

- (2) Mechanics Design and Systems Handbook
- (3) Apollo Reliability Prediction Estimation and Evaluations
- (4) MIL-HDBK 217A
- (5) Manufacturer

generator sets, more accurate values of mean time between failures than provided in this report should be obtained. It will be necessary to develop a data-collection and feedback system that will provide the proper historical information for improving design, lowering the cost of equipment repair, and reducing equipment downtime due to frequent failures.

4.2 DEVELOPMENT OF EQUIPMENT MAINTENANCE DATA

The information available for estimating component repair times is inadequate. Both manufacturers are planning systems with hermetically sealed organic-fluid loops; this will require that the generator set be transported back to a depot maintenance facility or the manufacturer for repair of any component that involves breaking this seal. The long-range development plans include making the systems repairable at the field maintenance facilities by providing the necessary loop-purging and fluid-charging equipment at that level.

The only equipments intended to be repairable by the user or support-level maintenance are system-support components and some of the power-generator components. The detailed design information concerning these areas is still being formulated by the manufacturers and is not yet adequate for developing realistic mean-time-to-repair (MTTR) values. However, STRATOS furnished a list of estimated repair times for the support components. The MTTR for organizational maintenance is 0.7 hour.

A detailed examination of system repairability should be made for each system, considering the present repair-level capabilities of both the prototype models and anticipated production models. Repair times can be obtained at the same time prototype testing is being performed, and recommended design improvements can be reflected in those values.

With the proper data-collection and feedback program, the best reliability, maintainability, and availability figures can be obtained for the prototype designs and reasonably accurate estimates made for final production models.

CHAPTER FIVE

FAILURE MODE AND EFFECT ANALYSIS

The Failure Mode and Effect Analysis (FMEA) is an integral part of the reliability prediction. It is a systematic examination of all components of the system to identify their functions and how they can fail and to determine the effects of each component failure on the overall system in relation to mission performance and personnel safety.

The identification of problem areas can lead to design changes that improve reliability and maintainability or produce savings for the entire program. Based on FMEA results program management can adjust the test and evaluation programs to provide maximum assurance that the probability of critical failures has been either eliminated or reduced to a tolerable level.

In an FMEA, mathematical probabilities of occurrence are normally assigned to the various failure modes. For this report, the FMEA is presented primarily to permit a better understanding of the Rankine-cycle systems and the interaction of the components. No attempt is made to assign failure-mode probabilities, because of the lack of historical data on equipment of this type, and only the more prominent failure modes are listed. Since there is no inherent redundancy in the system, most of the component failures have the same ultimate effect on the system — loss of power output. Tables 3 and 4 are the FMEAs for the organic Rankine-cycle engine generator sets of Fairchild Hiller Stratos Division and Thermo Electron Corporation, respectively.

The following elements comprise the FMEA format used:

- **Group Code Number** — the numbers assigned to each component or circuit in the reliability block diagrams in Section 3.3
- **Description of Component/Assembly** — the nomenclature of the components or circuits as specified by each manufacturer
- **Function** — the general description of each FMEA component's functioning in the system
- **Failure Mode** — the type of failure judged to have a probability of occurring during a mission
- **Failure Cause** — the most probable causes of the failure
- **Failure Effect** — the effect of the failure on the system and the mission
- **Criticality** — the severity of each failure mode and its related failure effect on a discrete phase of the mission:
 - **Critical (C)** — a failure that prevents the component from completing a discrete phase of the mission or is judged hazardous to personnel

- .. **Major (M)** — a failure that significantly degrades the performance of the component or delays its function such that it may not complete a discrete phase of the mission
- .. **Minor (m)** — a failure that does not have a significant effect on the ability of the component to complete the discrete phase of the mission, but should be repaired eventually
- **Action Taken/Avoidance Technique** — the action to be taken by the user to return the set to operational condition; or the technique that can be used during manufacture to eliminate, or minimize the effect of, the failure mode or to make the set easier to repair in the field

Table 3. FAILURE MODE AND EFFECT ANALYSIS FOR STRATOS ENGINE GENERATOR SET

| Group Code No | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|------------------|--|---|---|---|--|-------------------|---|
| FLUID LOOP-11000 | | | | | | | |
| 11010 | Boiler | Convert the working fluid (FC 75) from a liquid to a vapor; contain and muffle the burner flame | Rupture in working fluid tube | Overheating, fatigue, thermal expansion | Working fluid deterioration from overheating, causing corrosion in system components Loss of working fluid, causing system shutdown | M, C | Safety devices will prevent system damage from overheating by shutting system down. |
| | | | Ruptured boiler casing | Hot start, fatigue, thermal expansion | System shutdown, excessive noise | C | |
| 11030 | Start Valve | Restrict fluid flow in the system at start up until the prescribed vapor pressure and temperature is reached | (1) Failure to close; (2) Failure to open; (3) Failure to open or close completely | Corrosion, erosion, clogging from contamination of working fluid; broken spring, bellows, or plunger | (1) Failure to close; system start-up will be delayed, possible damage to turbo-alternator pump (2) Failure to open; system shut down by safety over-temperature sensors (3) Failure to open close completely; system output reduced by flow restriction | m, M C m, C | |
| 11040 | Modulation Valve | Control the flow rate of the working vapor to the turbine to maintain constant alternator RPM | Failure of valve to control flow | Valve frozen or jammed from contamination or corrosion Valve worn excessively from erosion, allowing excessive flow of vapor to turbine | Inability to regulate RPM and loss of output regulation | M, C | |
| 11050 | Turbo-alternator Pump (T-A P) | Contains a rotary engine (turbine) (1) on a rigid shaft with the alternator (2) which provides primary and accessory power and excitation for the field coils, and the feed pump (3) which increases the pressure of the working fluid prior to entering the boiler | (1) Failure of turbine (2) Failure of alternator primary power, accessory power (3) Failure of pump | Misalignment from bearing or spacer wear, causing vibration or contact with nozzle Open, grounded, shorted winding Cavitation, wear, corrosion of pump blades, intake, or exhaust ports | Deterioration of output until system shuts down Primary: reduction or loss of output power - system continues to operate Accessory: loss of system Reduction in pumping capability, causing reduced system output to system shutdown | M, C C C | |
| | | | Cracked, broken, leaking housing | Fatigue, shock, vibration, manufacturer's defect | Loss of working fluid, causing deterioration of output to system low-pressure shutdown | M, C | |
| 11060 | Regenerator assembly | Increase temperature of the working fluid before it enters the boiler by transferring heat from the working vapor after it leaves the engine | Housing rupture (vapor area) Finned-tube rupture (liquid area) Clogged fins on heat exchanger | Fracture at flow, or fatigue from vibration, shock, thermal expansion Deposit buildup on fins from working fluid contamination | Deterioration until system shuts down Reduced efficiency | C M | |
| 11070 | Mixing Section De-Super heater | Mix the fluid that has lubricated the T-A P bearings with the vapor before it enters the condenser | Ruptured housing; mixing section clogged, corroded, eroded | Fatigue, shock, vibration, contaminated working fluid, or thermal stress | Loss of working fluid, causing system shutdown; Improper mixing or buildup of back pressure on bearing lubrication, causing overheating of bearings | C M, C | |
| 11090 | Condenser | Convert the working fluid from a vapor to a liquid by removing heat | Leak, ruptured tube Clogged condenser tubes Clogging of cooling air fins | Fatigue from shock, vibration, or flow at weld Contamination from working fluid Atmospheric particle contamination | System shutdown Loss of output Loss of output | C m, M m | Quality control and testing to assure integrity of fabricated tubing, housing, and brazing. PFI tests of working fluid should detect contamination before critical buildup can take place. PFI includes periodic cleaning of condenser core fin area. |
| 11110 | Check Valve, Main | Prevent reverse working fluid flow at start-up | Failure to open Failure to close | Broken spring; ball jammed in orifice; opening clogged; or seat eroded, preventing ball from seating | Open: system will shut down from overpressurization Close: system will not start - possible damage to boiler or deterioration of working fluid from overheating | C C | |
| 11120 | Check Valve, Start up | Prevent working fluid reverse flow through the start pump during system operation | Failure to open Failure to close | Broken spring; ball jammed in orifice; opening clogged; or seat eroded, preventing ball from seating | Open: system cannot be started Close: reverse flow through start pump into condenser will reduce output and possibly cause system shutdown | C M, C | |
| 11130 | Pressure Regulator, Bearing Lubricator | Maintain a constant pressure flow of working fluid lubricant to the T-A P bearings | Failure to regulate the pressure | Worn parts, clogged, cracked casing | Low pressure: burn out T-A P bearings - system shutdown High pressure: overlubrication of bearings, causing fluid flow into alternator, possible viscous drag | M, C M, C | Pressure gage between regulator and bearings will give visual check |
| 11140 and 11150 | Starting Fluid Pump and Motor | Provide initial fluid pressure and flow to start the Rankine cycle engine generator set | Reduction in pump output capacity Failure to pump Pump cavitation | Worn motor brushes or pump motor bearings, or fluid leakage Motor failure from open, shorted, or grounded circuit or magnetic coupling failure Reverse or malfunction | Possible inability to start system Failure to start Failure to start | m, M C C | |

*C = Critical, M = Major, m = Minor. **11020 and 11090 are combined with 11100

Table 3. (continued)

| Group Code No. | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|-----------------------------------|---|--|---|---|--|--------------|--|
| 11150 | Drains, T-A-P | Drain fluid that leaks into the alternator back into the fluid loop | Drains clogged | Contaminated working fluid | Alternator fills with fluid. Viscous drag causes loss of output until system shuts down | C | |
| 11160 | Cooling Coil, Alternator | Transfer excess heat from the alternator to the working fluid | Ruptured or clogged working fluid tube | Fatigue, thermal stress, shock, vibration, or contaminated working fluid | Gradual loss of working fluid, causing eventual system shutdown | C | |
| 11170 | Cooling Coil, Power Conditioner | Transfer excess heat from the power conditioner to the working fluid | Ruptured or clogged working fluid tube | Fatigue, thermal stress, shock, vibration, or contaminated working fluid | Gradual loss of working fluid, causing eventual system shutdown | C | |
| 11020, 11090, 11180 | Thermistor Connections, Piping and Joints, and Bellows Tube | Connect the components in the fluid and allow for thermal expansion of the piping | Leak, rupture | Fatigue due to temperature, shock, vibration | Loss of working fluid, causing reduced output to system shutdown | m/C | Before the fluid loop is filled and sealed, a helium leak test should be performed to insure loop integrity. |
| 11190 | Pressure-Burst Disk | Safety device in fluid loop that ruptures to prevent excessive system over pressure if shutdown circuit fails | Fails below rated pressure Fails at rated pressure Fails above rated pressure | Manufacturing defect System overpressure-shutdown circuit fails, disk works as designed Manufacturing defect | Premature loss of system Loss of system with no damage to components in fluid loop Loss of system with possible serious component damage | C C C | Pressure-burst disks represent final safe system shutdowns before some fluid-loop component is damaged. System safety pressure shutdown must be calibrated with great care |
| 11210 | Pressure-Relief Valve | Functions in conjunction with the start-up valve (11030) to allow fluid to act on the bellows at the preset pressure | Valve fails to close Valve fails to open | Broken spring, ball jammed in orifice, opening clogged; or seat eroded, preventing ball from seating | Close: system start-up may be retarded, with possible damage to T-A-P Open: system shutdown by safety overtemperature sensor | m/M | |
| POWER GENERATION-14000 | | | | | | | |
| 14010 | Voltage Regulator VR1 | Receives power from PS2 and provides field-coil excitation for primary power circuits | Fails to regulate | Out of adjustment, regulator failure from thermal stress, shock, vibration | Output voltage out of specification to total loss of output | M/C | Modular replacement concept for electrical electronic circuits will minimize downtime and make unit unit-repairable. |
| 14020 | Voltage Regulator VR2 | Receives power from PS2 and provides field-coil excitation for accessories after nator | Fails to regulate | Out of adjustment, regulator failure from thermal stress, shock, vibration | Accessories output voltage out of specification to total loss of accessories power | M/C | See 14010 |
| 14030 | Voltage Regulator VR3 | Receives power from PS2 and provides regulation of 15W output for battery charging | Fails to regulate | Out of adjustment, regulator failure from thermal stress, shock, vibration | Improper charging of battery; eventual loss of battery power and capability to start system | M/C | See 14010 |
| 14040 | Power Conditioning Circuit PS1 | Three-phase, full-wave-rectifier bridge circuit converting primary ac to primary dc power output | Rectifier fails | Normal component failure - shock, vibration, thermal stress | Reduction in, to loss of, primary power | M/C | See 14010. |
| 14050 | Power Conditioning Circuit PS2 | Converts accessories power output from ac to dc for accessories use and for voltage regulators VR1, VR2, and VR3 | Rectifier fails | Normal component failure - shock, vibration, thermal stress | Loss of all power, system shutdown | C | See 14010 |
| 14060 | Power Conditioning Circuit PS3 | Converts ac accessories power to dc for operation of condenser fan motor | Rectifier fails | Normal component failure - shock, vibration, thermal stress | Condenser fan motor slows or stops running; depending on ambient temperature and load system, could cause operation to total shutdown | m/C | See 14010. |
| 14070 | Connector 2 pin | Connect Load to Generator Set | Connector pin breaks | Deterioration from environmental elements | Inability to connect load to set | m/M | In emergency connector can be jumpered. Repairable in use? |
| ELECTRONIC CONTROL CIRCUITS-16000 | | | | | | | |
| 16010 | Overvoltage Crowbar Circuit | Protect control circuit from over-voltage condition | Failure of circuit, open Failure of circuit, shorted | Failure of circuit component (resistor, shock, vibration, thermal stress, or random component failure) Same as above | Open: no effect unless circuit is needed, at which time control-circuit damage could result from overvoltage Shorted: will trip out circuit breaker, shutting system down | m/C C | Pre-test loop may be method of determining if circuit is available. See 14010 |
| 16020 | 30-Second Timer Circuit | Begin operating the start pump and boiler blower fan during system start up in order to prime the boiler with fluid and purge it of fuel vapor prior to ignition | Failure of circuit | Same as above | System will not start | C | See 14010 |

(continued)

Table 3 (continued)

| Group Code No. | Description of Component/ Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/ Avoidance Technique |
|-----------------|--|--|--|--|--|--------------|---|
| 16030 and 16140 | Overtemperature Circuit | Shut down system if working fluid temperature exceeds 700°F by shutting off fuel supply | False signal Failure to sense over-temperature condition | Same as above | System will shut down If safe shutdown is required and does not occur, system can be seriously damaged from overheating. Over speed circuit (6140) should function, first | C | See 14010 |
| 16010 | 3 Minute Timer Circuit | Pick up the start sequence from the 30 second timer circuit and provide the capability to start the system, coordinate all the machinery required for startup, remove machinery from loop on proper sequence of starting, and shut down on false start | Failure to control start-up sequence | Electrical-component failure due to temperature, vibration, shock, or random circuit failure | Failure to start system Failure to sequence startup mode properly - no problem, to no system start, or danger to personnel from boiler explosion | C m C | Module replacement of circuit would eliminate downtime and make system user-repairable Safety devices should be located to prevent ignition when large amounts of unburned fuel have been injected into boiler |
| 16050 and 16160 | Air and Fuel Rate Control Circuit | Sense working fluid temperature and determine the amount of air and fuel required to maintain the generator load and operate the combustion air fan and fuel pump to provide that amount | Loss of signal Loss of control, full open Loss of control, full closed | Open control circuit Failure of one or more circuit components | System shutdown or failure to start Full open - high boiler temperature; system continues to operate at full load, otherwise overpressure will cause safety shutdown Full closed - system shutdown or failure to start | C m C | See 14010 |
| 16060 and 16150 | Speed Control Circuit, Condenser Fan | Sense working fluid temperature at the condenser (11080) exhaust port, turning on the fan motor or increasing decreasing fan speed to maintain steady state flow | Failure of control circuit | Contamination and wear of the temperature sensor; open, short, grounded control circuit | Instability - loss of output regulation Failure open - motor continues to operate; system runs at reduced efficiency Failure closed - loss of fan cooling, temperature pressure rise causes safety shutdown of system | M M | See 14010 |
| 16070 | Speed Control Circuit Turbine | Sense the speed of the alternator and send a signal to the linear proportional solenoid, which moves the modulation valve to maintain constant RPM | Failure of control circuit | Open, shorted, grounded circuit due to failure of one or more circuit components | Loss of output regulation | M C | See 14010 |
| 16080 | Over-speed Circuit, Turbine | Shut system down by cutting off fuel supply should turbine overspeed | Failure of control circuit to sense over speed | Same as above | If overspeed condition occurs and the circuit does not function, the system runs until overtemperature shutdown occurs or feed pump cavitation occurs, output voltage will be uncontrollable | C C | Circuit characteristic may make it advantageous to incorporate the speed-control circuit with this circuit to improve system reliability See 14010 |
| 16090 | Control Connecting Circuit | Interconnect the control circuits forming an interlocking network to start, run, protect, and shutdown the generator set | Failure of control circuit | Circuit open, shorted, grounded from thermal stress, vibration, shock or normal life wearout | No immediate effect, to system shutdown or inability to start | m C | See 14010 |
| 16110 | Ultrasonic Atomizer Oscillator Circuit | Convert steady state dc into a pulsing circuit for the atomizer valve | Loss of signal output Improper signal output | Circuit component failure from thermal stress, vibration, shock or normal life wearout Deterioration of circuit component | Fuel not atomized into boiler, causing safety hazard and system shutdown Improper burning of fuel in boiler, deterioration to low of combustion and system | C M C | See 14010 |
| 16120 | Ignition Circuit | Provide the signal and current to the ignitor | Ignition loss | Open control circuit | System shutdown or failure to start | C | See 14010 |
| 16130 | Speed Control Linear Solenoid | Receive the signal from the speed control circuit (16070) and translate that into a linear motion to move modulation valve (11040) | Failure of solenoid | Open, shorted, grounded coil | Inability to control turbine speed | C | |

*16150 is combined with 16030. 16150 is combined with 16060. 16160 is combined with 16050.

(continued)

Table 3. (continued)

| Group Code No. | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|--------------------------|-----------------------------------|---|--|--|--|--------------|---|
| SUPPORT COMPONENTS-18000 | | | | | | | |
| 18010 and 18020 | Fuel Pump and Motor | Provide the proper quantity of fuel to the ultrasonic atomizer | Failure to supply fuel | Line clogged from contamination, broken fuel line from vibration, fatigue | System shutdown | C | Fuel-line filter should be incorporated into system |
| | | | Reduction in fuel supply | Motor winding shorted, grounded, open; pump gears jammed | Loss of regulation of voltage output | M | Fuel pump and motor should be designed for repair or replacement by user. |
| | | | | Line contamination | | | |
| | | | | Pump gears worn; motor/pump bearings worn, binding | | | |
| 18030 | Ultrasonic Atomizer | Atomize the fuel into the boiler for proper, efficient combustion | Atomizer clogged | Dirt in fuel | Improper burning of fuel in boiler; deterioration to loss of combustion and system | M/C | Fuel filter should be added to system to remove dirt from fuel. |
| | | | Atomizer failure | Coil shorted, grounded, or open | Fuel not atomized into boiler, causing safety hazard and system shutdown | C | Atomizer is user-reparable. |
| 18040 and 18050 | Combustion Air Fan and Motor | Supply the combustion air to the boiler for complete combustion of the fuel | Motor failure | Worn out brushes, windings shorted/open from excessive ambient temperature | Reduction of combustion air pressure, causing a reduction in output to total loss of system | M/C | Fan and motor should be designed for repair or replacement by user. |
| 18060 | Igniter | Provide the spark to ignite the fuel in the boiler | Failure to ignite fuel | Spark plug opened, shorted, grounded (contamination) worn | System shutdown or failure to start | C | Clean or replace plug. |
| 18070 and 18080 | Condenser Fan and Motor | Force cooling air to flow across the core fins of the condenser | (1) Motor failure | Worn bearings, open or shorted winding, worn brushes | (1) Deterioration of output to system shutdown by safety if motor stops completely | M/C | |
| | | | (2) Fan failure | Worn bearings | (2) Increase in noise level with worn bearings | | |
| 18090 | Ducting | Channel the intake air to the boiler and the exhaust from the boiler | Cracked or ruptured ducting | Shock, vibration, thermal stress | Intake reduced air flow to boiler; full power output may not be achievable Exhaust: damage to components adjacent to duct personnel and fire hazard | m/M | Ducting can be repaired or replaced by user. |
| 18110 | Batteries, 24 Volts | Provide 24 Vdc starting current and winterization warm-up prior to starting | Loss of charge | Breakage, loss of electrolyte; surface or internal short. | Winterization battery can be used to start system if available; if no outside starting source exists, the generator set cannot be started | M/C | System can be jumper-started by a standard 24 volt military truck battery |
| 18120 | Fuel Lines and Fittings | Conduct the fuel from the fuel tank to the fuel pump and then to the atomizer | Fuel line clogged, leaking, ruptured | Contamination in fuel, vibration, shock | Possible loss of output regulation at full load to total loss of system | m/C | Visual inspection should show leaks. Fuel line should be user-reparable. |
| 18130 | Fuel-Line Filter | Filter contaminants from the fuel | Filter screen clogged | Contaminants in fuel | Reduction in output | m/M | Clean filter during regularly scheduled PM |
| 18140 | Fuel Tank and Shut Off Valve | Contain an eight-hour fuel supply | Tank leaking, cracked, ruptured; valve clogged, jammed, broken | Vibration, shock, thermal stress | Leaking fuel could cause fire hazard System should be shutdown for immediate repair | m/C | Visual inspection should show leaks. Tank should be user-replaceable. |
| 18150 | | | Filter screen deteriorated, cracked, broken | Vibration, shock, fatigue | Clogged atomization burner, causing reduction in output to loss of system | m | Replace damaged filters during PM. |

*18150 is combined with 18140.

Table 4 FAILURE MODE AND EFFECT ANALYSIS FOR TECO ENGINE GENERATOR SET

| Group Code No | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|------------------|-----------------------------------|---|---|---|--|----------------------------|--|
| FLUID LOOP-21000 | | | | | | | |
| 21010 | Boiler (Cyl. Jacket and Casing) | Convert the working fluid (CF31) from a liquid to a vapor, separate the working fluid from the buffer fluid, and retain and muffle the burner flame | Rupture in working-fluid tube Rupture in buffer fluid tube Ruptured boiler casing | Overheating, fatigue, thermal expansion Overheating, fatigue, thermal expansion Hot start, fatigue, thermal expansion | Working fluid deteriorated by mixing with buffer fluid, causing gradual reduction in output Working fluid hot spots due to loss of buffer fluid, causing gradual reduction in output System shutdown resulting from buffer fluid's extinguishing flame System shutdown | M/C M C C C | Safety devices will prevent system damage due to over pressurization by shutting system down |
| 21040 | Separator Assembly | Separate the silicone lubricant from the working fluid and return the lubricant to the engine crankcase | Collector screen clogged Collector screens cracked, broken Float valve fails full closed Float valve fails full closed Float valve sticking Rupture or failure at joints | Deposit buildup on screen from working-fluid contamination Fatigue, shock, vibration Deposits and particles from fluid/oil contaminant, in Mechanical linkage broken, jammed, disconnected Particle contamination Fatigue, shock, vibration, thermal expansion | Reduced efficiency Oil carried throughout the system, loss of lubricating function, slow progression to shutdown Working fluid flows into crankcase - output falls off Oil carried throughout the system, loss of lubricating function, rapid progression to shutdown Loss of system efficiency Deterioration to shutdown | M M M C M C | Placing sight glass on tank could give visual-inspection capability during operation. Pressure gage should indicate fluid loss prior to shutdown |
| 21010 and 21130 | Throttle Valve and Driving Motor | Throttle the working fluid flow to control expander rpm | Valve sticking or leaking No control Bellows rupture | Contamination in working fluid, rupture in O-ring Drive motor open, shorted, grounded Fatigue due to vibration, shock, temperature, initial flow | Deterioration in output regulation Output deterioration to system shutdown System shutdown by over pressure safety | M M C C | |
| 21050 | Expander Engine | Convert working vapor flow energy into rotational shaft motion to drive alternator | Wear of valves, bearings, and rings, metal fretting Leakage, static or dynamic Shaft bearing seizing and fracturing Housing rupture | Contaminated lubricant, natural mechanical wear due to age Seizing or failure of shaft rotary seals Shaft bearing defect, wear, and fatigue Fatigue, defect of casting | Increase noise level, loss in energy-conversion efficiency Static leak results in influx of contaminants to the system, dynamic leak results in loss of working fluid, thus a drop in system output System shutdown System shutdown, loss of working fluid | m M M C C | Increased noise indicates serious wearing of parts Rate of fluid flow from reservoir will indicate system fluid loop integrity Maximum requirements should be established prior to system-integrity testing |
| 21060 | Regenerator Assembly | Increase the working fluid's temperature before it enters the boiler by transferring heat from the working vapor after it leaves the engine | Housing rupture (vapor area) Finned-tube rupture Clogged fins on heat exchanger | Fracture at flow, or fatigue from vibration, shock, thermal expansion Deposit buildup on fins from working-fluid contamination | Deterioration to system shutdown Reduced efficiency | C M | Quality control and testing to assure integrity of fabricated tubing, housing, and brazing |
| 21170 | Condenser | Convert the working vapor to a fluid by removing heat | Leak, ruptured tube Clogged condenser tubes Clogging of cooling air fins | Fatigue from shock, vibration or flaw at weld Contamination from working fluid Atmospheric-particle contamination | System shutdown Loss of output Loss of output | C m M m | Quality control and testing to assure integrity of fabricated tubing, housing and brazing PM tests of working fluid should detect contamination before critical buildup can take place PM includes periodic cleaning of condenser-core (in area) |
| 21140 | Feed Pump | Raise the pressure of the working fluid before it enters the boiler | Worn valves, seals and bearings, fatigue in springs Rupture - loss of working fluid or lubricant Failure of pump to operate | Contaminated lubricant and working fluid, natural mechanical wear from age and seals Shaft fracture, pulser seizing, or gear breakage due to flow or fatigue and excessive wear from lube-oil failure | Increased noise level, reduced output System shutdown Complete loss of pressurization causing system shutdown | m M C C | Increased noise indicates serious wearing of parts |
| 21170 | By-Pass Valve | Bypass excessive fluid pressure from feed pump back to the condenser | Fail closed Fail open Rupture of housing | Mechanical wear Fatigue from shock, vibration, thermal stress, and/or flaw in manufacturing | Fail closed - pressure in boiler increases until safety pressure switches shut down system Fail open - condenser pressure increases Loss of working fluid causing system shutdown | C C C | |

**21020 and 21040 are combined with 21160

(continued)

| Table 4 (continued) | | | | | | | |
|---|---|---|--|--|---|-----------------|---|
| Group Code No. | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
| FLUID LOOP-21000 (continued) | | | | | | | |
| 21120 | Starting Fluid Control Reservoir | Provide a fluid reservoir for the start pump (21130) and the feed pump (20090) to prevent pump cavitation | Leaking, ruptured reservoir Float valve fails to operate | Fatigue from vibration, shock Mechanical linkage broken, jammed from erosion or deposits from contaminated fluid | Loss of fluid, causing system shutdown Valve failed closed, system will not start Valve failed open, reduction of system output | M/C M/C | Pressure-burst disks represent final safe system shutdown prior to damaging some fluid-loop component. System safety pressure shutdown must be calibrated with great care. Before the filling and sealing of the fluid loop, a static pressure test should be performed to ensure loop integrity. |
| 21130 and 28140 | Starting Fluid Pump and Motor | Provide initial fluid pressure and flow to start the Kamikaze cycle engine generator set | Reduction in pump output capacity Failure to pump Pump cavitation | Worn motor brushes, pump motor bearings, or fluid leakage Motor failure from open, shorted, or grounded circuit or magnetic coupling failure Reservoir (21120) malfunction | Possible inability to start system Loss of regulation of output Failure to start Failure to start | m/M m/M C | |
| 21140 21170 and 28170 | Pressure Burst Disks 100, 800, 2000 psi | Safety device in fluid loop and buffer fluid line which ruptures to prevent excessive system overpressurization if safety-pressure shutdown circuit fails | Fails below rated pressure Fails at rated pressure Fails above rated pressure | Manufacturing defect System over-pressure shutdown circuit fails, disk works as designed Manufacturing defect | Premature loss of system Loss of system with no damage to components in fluid loop Loss of system with possible serious component damage | C C | |
| 21020 21090 21150 and 21180 | Thermistor and Pressure Sensor Connections, Lines and Fittings, and Flexlines | Connect the components in the fluid loop | Leak, rupture | Fatigue due to temperature, shock, vibration | Loss of working fluid, causing reduced output to system | M/C | |
| POWER GENERATION - 24000 | | | | | | | |
| 24010 and 24020 | Alternator Starting Motor | Generate the output power of the system, provide internal power for sustained system operation, and act as a starting motor for the system feedpump at system startup | Deterioration to loss of a-c output voltage Loss of starting torque | Generator windings open, shorted, grounded; worn or open circuit in AC slip rings, bearing failure D-c field circuit open, shorted, grounded | Reduced voltage regulation to no system output Progressive degradation resulting in inability to start | M/C | System can be pump-started with a standard 24-volt military battery |
| 24030 | Rectifier and Battery Charging Circuit | Charge the battery after system startup | Failure of battery-charging circuit | Electronic component failure due to temperature, shock, vibration, or random circuit failure | Spare battery can be used to start system if available but must be charged by other means. If there is no outside starting source, the generator set cannot be started. | M/C | |
| ELECTRONIC CONTROL CIRCUITS - 26000 | | | | | | | |
| 26010 26040 | Speed Sensing and Throttle Valve Logic Circuit | Sense alternator (24010) frequency and load and adjust the throttle valve (21040 and 28130) to maintain constant RPM | Loss of signal, fail full-open command, fail full-closed command | Electrical-component failure (catastrophic or drift) due to temperature, vibration, shock, or random circuit failure | Loss of signal, full-open command - overspeed, loss of regulation, and ultimate system shutdown due to overpressure Full-closed command - Loss of regulation, slow speed, system shutdown due to overpressure | M/C M/C | Modular replacement of control circuit would minimize system downtime and make unit war-repairable. |
| 26020 | Burner Control and Ignition Logic Circuit | Provide the signal and current to the igniter and burner | Instability - loss of control Ignition loss Loss of control, full open Loss of control, full closed | Electronic-component deterioration Open control circuit Failure of thermistor, relay, solenoids, or other circuit components, or combination of these | Instability - loss of output regulation System shutdown or failure to start Full open - high boiler temperature, system continues to operate if at full load; otherwise, overpressure will cause safety shutdown Full closed - low boiler temperature; system inability to handle full load with required regulation | M C M/C | |
| 26030 and 26090 | Fuel Rate Logic Circuit | Determine the amount of fuel required to maintain the generator load and operate the fuel pump to provide that amount | Loss of signal Loss of control, full open Loss of control, full closed | Open control circuit Failure of one or more circuit components | System shutdown or failure to start Full open - high boiler temperature; system continues to operate at full load; otherwise, overpressure will cause safety shutdown Full closed - system's shutdown or failure to start | C M/C | |

(continued)

Table 4 (continued)

| Group Code No | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|---|--|--|--|--|---|-------------------|--|
| ELECTRONIC CONTROL CIRCUITS - 26000 (continued) | | | | | | | |
| 26050 and 26110 | Pressure-Control Condenser Fan Logic Circuit | Sense working fluid pressure at the condenser (21070) discharge, turning on off the fan motor or increasing/decreasing fan speed to maintain steady state pressure | Failure of control circuit | Contamination and wear of the pressure sensor, open, short, grounded control circuit | Instability - loss of output regulation Fail open - motor continues to operate, system runs at reduced efficiency Fail closed - loss of fan cooling, temperature pressure rise causes safety shutdown of system | M Q C | Modular replacement of control circuit would minimize system downtime and make unit user-repairable |
| 26060 | Overtemperature Circuit | Sense fluid temperature at boiler discharge and safety shutdown the system by cutting off the fuel supply should temperature exceed preset limit | False signal Failure to function on overtemperature | Failure of circuit component or thermistor Improper wiring, deterioration of thermistor | System will shutdown Pressure burst disc will actuate. System will shut down and be rendered useless | C M C | Modular replacement of control circuit would minimize system downtime and make unit user-repairable Press-to-test capability should be installed if possible |
| 26070 | Starting Logic Circuit | Provide the capability to start the system, coordinate all the machinery required for start-up, remove machinery from loop on proper sequence of starting, and shutdown on false start | Failure to control start-up sequence | Electrical-component failure due to temperature, vibration, shock or random circuit failure | Failure to start system Failure to sequence startup mode properly - no problem to no system start or danger to personnel system from boiler explosion | C M C | Modular replacement of control circuit would minimize system downtime and make unit user-repairable Safety devices should be located to prevent ignition when large amounts of unburned fuel have been injected into boiler |
| 26080 | Control Coasting Circuit | Interconnects the control circuits forming an interacting network to start, run, protect, and shut down the generator set | Failure of circuit | Circuit open, shorted, grounded component failure from thermal stress, vibration, shock or normal life wearout | No immediate effect to system shutdown or inability to start | M C | Modular replacement of control circuit would minimize system downtime and make unit user-repairable |
| SUPPORT COMPONENTS - 29000 | | | | | | | |
| 29010 and 29020 | Fuel Pump, Fuel Reservoir and Solenoid | Provide the proper quantity of fuel to the atomization burner | Failure to supply fuel Reduction in fuel supply | Line clogged from contamination, broken fuel line from vibration fatigue, solenoid pump open circuit Diaphragm valve leak, line contamination | System shutdown Loss of regulation of voltage output to atomizer | C M | Fuel-line filter checked and cleaned Fuel transfer pump should be designed for repair or replacement by user |
| 29030 | Fuel Line Filter | Filter contaminants from the fuel | Filter screen clogged Filter screen deteriorated, cracked, broken | Contaminants in fuel Vibration, shock, fatigue | Reduction in output Clogged atomization burner causing reduction in output to loss of system | M C C | Clean filter during regularly scheduled PM Replace damaged filters during PM |
| 29040 | Burner Assembly | Produce the flame to heat the working fluid | Poor combustion Loss of fuel | Deterioration of burner parts from progressive oxidation Poor fuel quality | Gradual reduction in output System shutdown or failure to start | M C | Preventive maintenance checks should detect deterioration before major problem occurs Clean or replace fuel-line filter, drain and refill fuel tank |
| 29050 | Atomization Compressor and Motor | Compress the air that is used to atomize the fuel and inject the mixture into the boiler | Ruptured diaphragm Motor failure | Deterioration, fatigue Worn end brushes Windings shorted open due to excessive ambient temperature | System shutdown Reduction in output System shutdown | C M C C | Compressor and motor should be designed for repair or replacement by user |
| 29060 | Atomizer | Reduce the fuel to fine particles in a spray for injection into the burner | Failure to atomize fuel properly | Clogged, worn by contaminants in fuel | Improper combustion in boiler, causing reduced output to loss of system | M C | Periodic cleaning of atomizer |
| 29070 and 29080 | Combustion Blower and Motor | Supply the combustion air to the boiler for complete combustion of the fuel | Motor failure | Worn end brushes, windings shorted open due to excessive ambient temperature | Loss of air pressure, causing a reduction in output, burner flame would be sustained at reduced efficiency by atomization and available air | M M | Compressor and motor should be designed for repair or replacement by user |
| 29090 | Igniter | Provide the heat to ignite the fuel in the burner | Loss of ignition | Glow-plug electrode opened, shorted, or grounded (contamination) | Failure to start | C | Clean or replace plug |
| 29110 and 29120 | Combustion Fan and Motor | Draws cooling air to flow around the combustion chamber | Motor failure | Worn bearings, open or shorted winding, worn brushes | Deterioration of output to system safety shutdown if motor is complete failure Increase in noise level from worn bearings | M C | Fan and motor should be designed for repair or replacement by user |
| 29130 | Battery (24 Volt) | Provide starting current | Loss of charge | Breakage - loss of electrolyte Surface or internal short | Spare battery can be used to start system. If no outside starting source exists, the generator set cannot be started | M C | System can be manually started from a standard 24 volt military battery |

* 29060 is combined with 29050, 29110 is combined with 29050, 29120 is combined with 29110, 29130 is combined with 29110.

(continued)

Table 4 (continued)

| Group Code No. | Description of Component/Assembly | Function | Failure Mode | Failure Cause | Failure Effect | Criticality* | Action Taken/Avoidance Technique |
|--|-----------------------------------|---|---|--|---|--------------|--|
| SUPPORT COMPONENTS - 28000 (continued) | | | | | | | |
| 28160 | Expansion Tank Boiler Jacket | Act as a reservoir for the buffer fluid and provide an area for thermal expansion during boiler operation | Leaking or rupture in tank | Fatigue, vibration, shock, excessive thermal expansion | Loss of buffer fluid, gradual reduction in operation to system shutdown | M/C | Unit designed to withstand pressure temperature beyond the limit where the working fluid/temperature pressure would cause system safety shutdown |
| ** 28180 | Fuel Lines and Connections | Conduct the F-4 from the fuel tank to the atomizer through the fuel pump | Fuel Line clogged, leaking, ruptured | Contamination in fuel, vibration, shock | Possible loss of output regulation at full load to total loss of system | m/C | Visual inspection should show leaks. Fuel Line should be user-replaceable. |
| 28190 | Fuel Tank and Shutoff Valve | Contain an eight-hour supply of fuel | Tank leaking, cracked, ruptured; valve clogged, jammed, broken | Vibration, shock, thermal stress, contaminated fuel | Leaking fuel could cause fire hazard. System should be shutdown for immediate repair | m/C | Visual inspection should show leaks. Tank should be user-replaceable. |
| 28210 | Ducting | Channel the intake air to the boiler and the exhaust from the boiler | Cracked or ruptured | Shock, vibration, thermal stress | Intake: reduced air flow to boiler; full power output may not be achievable Exhaust - damage to components adjacent to ducting; personnel and fire hazard; increase in noise | m/M | Ducting can be repaired or replaced by user. |
| 28220 | Pressure switches | Shut system down if 100 psi or 2000 psi pressure limit discs rupture | Failure to function when limit disc ruptures Premature Failure | Manufacturing defect Open, shorted, or grounded circuit | Possible system damage from delayed shutdown Loss of system from false safe - shutdown | m/M C | Incorporation of a pre-test circuit may detect unsafe factory switch. |

**28170 is combined with 28140.

CHAPTER SIX

COMPUTER PROGRAM

The computer program was developed on a time-sharing system with basic FORTRAN used as the language. This made the program suitable for use on USAMERDC's COMSHARE time-sharing system with their preferred XTRAN language.

The program, described and illustrated in Appendix B, is designed to assess the reliability of a simple series system. It can assess individual component redundancy when the appropriate inputs are provided for the redundant elements. Four reliability or failure distributions can be manipulated in the program: the exponential, normal, lognormal, and probability distributions. It is not necessary for all components to have the same distribution, but one component cannot have two failure distributions at one time. The four individual K factors can be applied to the single component failure rate to account for different system environments.

Appendix B also presents detailed instructions for exercising the program on a time-sharing computer terminal.

CHAPTER SEVEN

RELIABILITY AND AVAILABILITY PREDICTIONS

7.1 RELIABILITY PREDICTIONS

Reliability-prediction models were developed to represent the organic Rankine-cycle engine generator sets of Fairchild Hiller/Stratos Division and Thermo Electron Corporation. From these models, a computer program was derived; it yielded quantitative reliability predictions for the two systems.

Table 5 shows the specific results of the computer program for the two manufacturers' generator sets, operating for the two specified missions in the three environments.

| Table 5. RANKINE-SYSTEM PREDICTED RELIABILITY | | | | |
|---|-----------|--------|-----------|--------|
| K Factor | Mission 1 | | Mission 2 | |
| | STRATOS | TECO | STRATOS | TECO |
| Manufacturer | 0.9882 | 0.9941 | 0.9516 | 0.9757 |
| Portable | 0.9703 | 0.9766 | 0.8819 | 0.9061 |
| Track Vehicle | 0.8752 | 0.8990 | 0.5736 | 0.6415 |
| Laboratory | 0.9950 | 0.9948 | 0.9794 | 0.9787 |

It can be seen that the more severe the environment, the lower the probability that the generator set will achieve the stated mission. The manufacturers' estimates for their own system reliability are also included for comparison purposes. An examination of their data and the final results indicates that they assumed a fixed ground installation rather than one in which the Rankine system would be portable.

There is little significant difference in the system predicted reliabilities for either manufacturer for any given environment and mission. Operational analysis and accumulated failure data may yield different empirical results.

7.2 AVAILABILITY PREDICTION

The goal is to achieve a system inherent availability of 98 percent for each of the Rankine-cycle generator sets. Inherent availability is based on active operating and repair time and is the probability that the system will operate satisfactorily when called upon.

Mathematically, it can be defined as

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where

A_i = Inherent availability

MTBF = Mean time between failures (hours)

MTTR = Mean time to repair (hours)

Since a large portion of the organic Rankine-cycle generator set will not be repairable at the organizational level of maintenance, the estimate of the steady-state inherent availability is calculated as follows:

$$A_{(t)} = \frac{MTBF \text{ (repairable components)}}{MTBF + MTTR \text{ (repairable components)}} \times R_i \text{ (nonrepairable components)}$$

Table 6 shows the results of the availability predictions for the portable ground environment (K_2) for the 24 hour mission only. The maintainability information needed to derive the inherent availability was not available at the time this report was prepared, except for the STRATOS MTTR estimate of 0.7 hour; the maximum specified downtime of three hours was therefore used to compare the impact of repair on both systems' availability.

| Table 6. ESTIMATED STEADY-STATE INHERENT AVAILABILITY | | | | |
|--|-----------------|-----------|-----------------|-----------|
| MTTR Source | STRATOS | | TECO | |
| | MTTR (Hours) | $A_{(t)}$ | MTTR (Hours) | $A_{(t)}$ |
| Manufacturer | 0.7 | 0.9171 | — | — |
| Contract Goal | 3.0 | 0.9709 | 3.0 | 0.9783 |

Because of the large number of nonrepairable components and the high MTBF for the repairable components, the availability prediction differs only slightly from the reliability prediction.

CHAPTER EIGHT

FLUIDIC-CONTROL APPLICATION

In the present concept the organic Rankine-cycle engine generator sets will be controlled with electronic circuits. Since electronic circuits can fail catastrophically, another method of system control is being investigated — the use of fluidic components that are powered by the organic fluid's vapor pressure. The investigation to date has considered only the electronic circuits proposed by the two manufacturers.

The critical question is whether fluidic circuits can completely take the place of electronic circuits in the generator set. It is possible, but it is also believed that complete fluidic control is not practical. Fluidic circuits cannot compete with electronics in response time. Electronic responses are in microseconds and fluidics in milliseconds. Fluidic circuits are also usually larger than their electronic counterparts.

Yet fluidics has some advantages over electronics in that the controls can be hermetically sealed in the fluid loop. Contamination would be minimized, and there would be no dust or atmospheric corrosion to affect relay contacts, open leads, or solder joints. There are few moving parts in a fluidic circuit, as there are in electronic relays or stepping switches. Vibration is not a problem since the fluidic circuits are stacked and then fusion-bonded, forming an extremely rugged device.

In the organic Rankine-cycle generator sets, the best areas for the fluidic circuits are those in which pressure, temperature, or speed is being sensed and being converted to motion to regulate flow. The circuits in the system that detect fluid pressure and convert it to an output signal to control the condenser-motor, fuel-pump, and blower-motor speeds are best left as electronic circuits. These are electrical-signal input and output circuits; present fluidic circuits are not as compact, and their response time is slower.

The reliability of fluidic circuits is still in the very early prediction stage. Very little operational information has been accumulated on the circuits because of their still-limited use. It is known that leaks and contamination are the most prevalent failure modes, and it is believed that fusion-bonding the fluidic circuit and hermetically sealing the unit into the Rankine fluid loop would virtually eliminate these failure modes.

With the organic Rankine-cycle generator sets in the development stage, it may be premature to consider fluidic circuits. Each engine manufacturer is still making design changes, fluid-loop conditions are being revised, and the exact method of system control is still unknown in some instances. The design and fabrication of a fluidic circuit in itself is a complex effort because of the many unknowns and the lack of off-the-shelf standardized components.

The feasibility of fluidic circuits should definitely be investigated and tentative designs established for the use of fluidic controls on the generator sets. The actual incorporation of partial fluidic controls should take place only when the organic Rankine-cycle generator sets function properly and demonstrate their practicality for use as field mobile power sources.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this program was to provide USAMERDC with a quantitative appraisal of the predicted reliability of two organic Rankine-cycle engine generator systems. The tasks performed to meet this objective led to the following conclusions:

- The two manufacturers are constructing generator sets under different power requirements. Care should be exercised in making comparisons. The predictive results show little significant difference between the reliabilities of STRATOS's or TECO's Rankine systems.
- The electronic control circuits had extremely high failure rates and contributed heavily to system unreliability. TECO is still designing its control circuits; therefore, the STRATOS failure rates were used for the yet undesigned circuits. In this way, the impact is the same on both manufacturers. When TECO completes its design, the TECO model can be modified.
- The failure rates used in this project are estimates based on historical data from similar equipment. Until firm system failure data are developed, the results should not be considered empirical.
- The hermetically sealed fluid loops cause the major portion of the generator sets to be nonfield-repairable. This contributes heavily to system unavailability.

ARINC Research Corporation recommends the following courses of action based on the results of the analysis:

- Implement a data-collection and feedback procedure for MERDC and the manufacturer's testing program of the organic Rankine-cycle engine generator set.
- Perform a detailed design analysis of the Rankine systems to determine the best areas for design improvement, redundancy of components, and repairability to improve reliability, maintainability, and availability.
- Begin developing a life-cycle cost program to evaluate the proposed designs for portable field generator sets against those now in use. The evaluations should consider as a minimum initial production and procurement costs, operational costs, and the effects of repairability, logistics, reliability, and maintainability.
- Make a critical evaluation of fluidic circuits versus modular-replacement electronic circuits for the Rankine generator sets. The present estimates of control-circuit reliability may make fluidic circuits a wise choice.

APPENDIX A

SOURCES OF FAILURE-RATE DATA

APOLLO Reliability Prediction, Estimation, and Evaluation Guidelines, National Aeronautics and Space Administration, December 1963.

RADC-TR-114, Volumes I, II, and III, *Data Collection for Nonelectronic Reliability Handbook*, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York, June 1968.

Failure Information Notebook, Special Technical Report No. 32, ARINC Research Corporation, December 31, 1965.

Mechanical Design and System Handbook, Harold A. Rothbart, McGraw-Hill Book Company, New York, 1964.

MIL-HDBK-217A, *Reliability Stress and Failure Rate Data for Electronic Equipment*, Department of Defense, 1 December 1965.

Army, Navy, Air Force and NASA FARADA Failure Rate Data Program, Volumes 1, 2, 3, and 4, Naval Fleet Missile Systems Analysis and Evaluations Group, Corona, California.

APPENDIX B

COMPUTER PROGRAM FLOW CHART AND INSTRUCTIONS FOR USE

FLOW CHART

The flow chart for the computer program is presented in Figure B-1.

INSTRUCTIONS FOR USE ON TIME-SHARING COMPUTER TERMINAL

The steps described herein must be strictly adhered to for the program to function properly.

When a link with the time-sharing system is established, the first symbol seen after "RUN" is typed is an equal(=) sign. After the equal sign, type the number of components (N) in the system and the number of cycles of operation (M) (ten maximum). Each of these variables is allocated two places, and the data must be right-justified.

A second equal sign will then appear, and the M sets of times of operation must be typed. Each set consists of two times, a startup time and a run time, in units of hours. Each time is allocated five places; it must be typed with a decimal place and in such a way that none of the five-digit fields overlap.

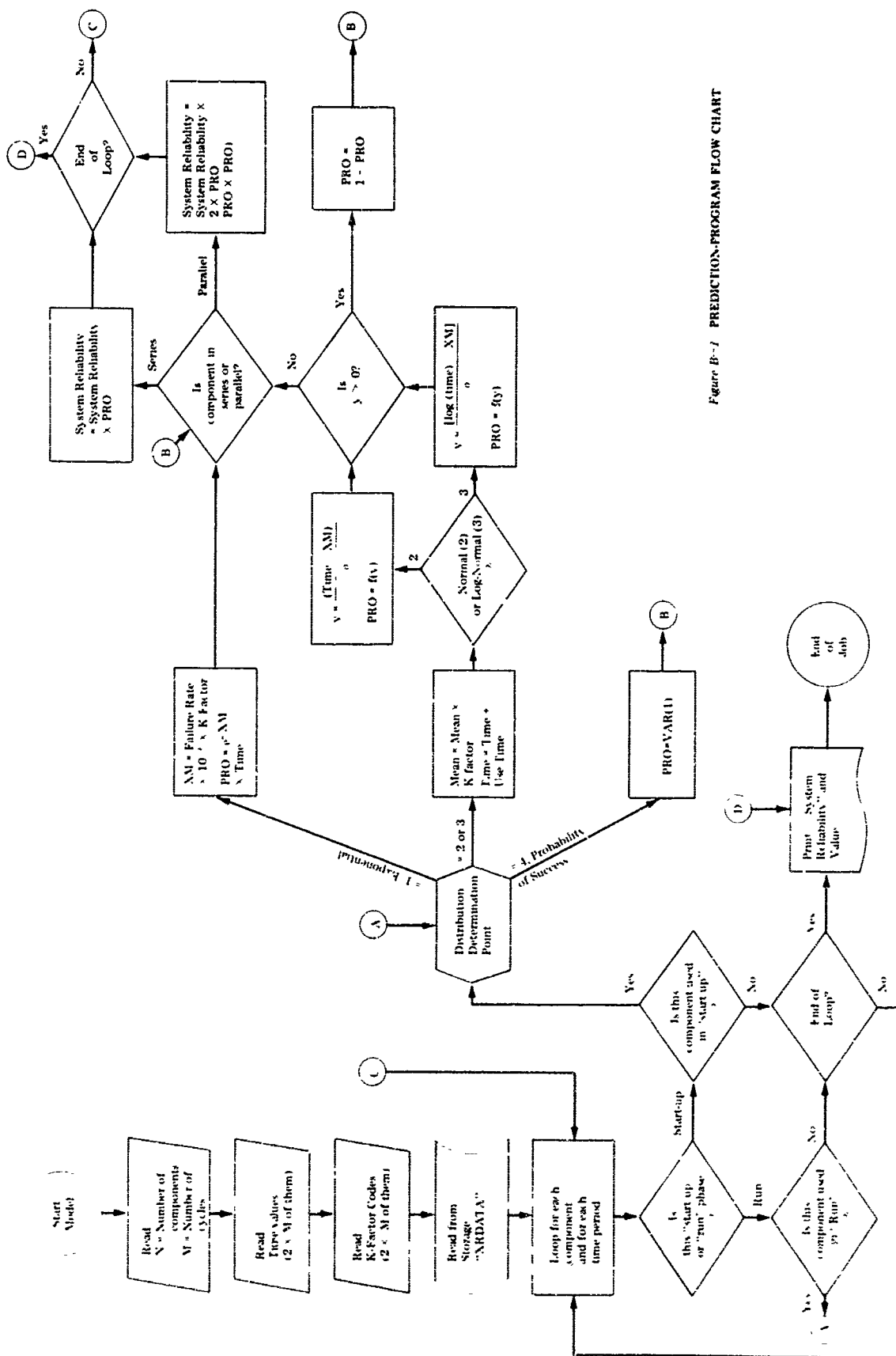
The third and last equal sign will appear, and the K-factor codes (1 to 4) must then be punched for the M cycles of operation. These factors are used to adjust the failure rate and mean values. There must be K factors for both startup and run; each K factor is punched in an I2 format. This ends the data entry at the keyboard at the time of execution.

The failure rates, means, accrued operating time, and K factors are stored as file and called "XRDATA" for Fairchild/Stratos and "YRDATA" for Thermo Electron. Before running the program (XMODEL), it is necessary to type the following line if the data file for Fairchild/Stratos is to be used: 90 READ ("XRDATA", 4) (ISP(I, 1), ISP(I, 2) IDST(I), (VAR(I, J), J = 1, 7), I = 1, N).

The term XRDATA must be changed to YRDATA if the Thermo Electron data file is used.

When the data are prepunched, the following format is used, where one line represents one component:

- Columns 1-5 contain a line number code. This is not used by the model program but is used to edit and update data entries.



- Column 8 contains a "1" if the component is in series and a "2" if it is in parallel.
- Column 11 contains a "1" if the component is used in startup only, a "2" if it is used during run only, and a "3" if it is used for both phases.
- Column 14 contains the distribution codes:
 - 1 = exponential
 - 2 = normal
 - 3 = lognormal
 - 4 = probability of success
- Columns 15–21 contain the exponential failure rate $\times 10^6$, or the mean time to failure (normal or lognormal), or the probability of the component's success.
- Columns 22–28 contain the standard deviation (normal or lognormal) or are set to 0.
- Columns 29–35 contain the time the component has already operated if normal or lognormal is used or are otherwise set to 0.
- Columns 36–42 contain K factor number 1.
- Columns 43–49 contain K factor number 2.
- Columns 50–56 contain K factor number 3.
- Columns 57–63 contain K factor number 4.

Note 1: The last seven fields must be punched with a decimal point, and no fields may overlap.

Note 2: The values associated with lognormally distributed variables must be in terms of natural logarithms.

The prediction program is shown in Figure B-2.

```

10  DIMENSION ISP(75,2),IDST(75),VAR(75,7),T(20),IOP(20)
15  FILENAME FRDATA,XRDATA,YRDATA,ZRDATA
20  READ 1,N,M
30  1 FORMAT(2I2)
40  M=244
50  READ 2,(T(I),I=1,M)
60  2 FORMAT(10F5.0)
70  READ 3,(IOP(I),I=1,M)
80  3 FORMAT(20I2)
90  READ("YRDATA",4)(ISP(I,1),ISP(I,2),IDST(I),(VAR(I,J),J=1,7),I=1,N)
100  4 FORMAT(5X,3I3,7F7.2)
110  PRINT:"PHASE AND SYSTEM RELIABILITIES, AND PHASE OPER. TIME"
120  S=1.0
130  DO 10 J=1,M
140  P=1.0
150  XM=J
160  ZM=ZM/2.0
170  IM=XM
180  DO 200 I=1,N
190  IF(J-244) 17,18,17
200  17 IF(ISP(I,2)-2) 19,200,19
210  18 IF(ISP(I,2)-2) 200,19,19
220  19 IJ=IOP(J)+3
230  II=IDST(I)
240  GO TO (21,22,22,24),II
250  21 XM=VAR(I,1)/1000000.0*VAR(I,IJ)
260  PR0=(EXP(-XM*T(J)))
270  GO TO 20
280  22 XM=VAR(I,1)*VAR(I,IJ)
290  TIME=T(J)+VAR(I,3)
300  IF(II-2) 25,25,23
310  25 Y=(TIME-XM)/VAR(I,2)
320  GO TO 26
330  23 Y=(ALOG(TIME)-XM)/VAR(I,2)
340  26 PR0=0.5*(1.0+(1.0-EXP(-0.63662*Y*Y))*0.5)
350  IF(Y) 20,20,28
360  28 PR0=1.0-PR0
370
380  GO TO 20
390  24 PR0=VAR(I,1)
395  20 IF(ISP(I,1)-1) 27,27,29
397  27 P=P*PR0
400  GO TO 200
403  29 P=P*(2.0*PR0-PR0*PR0)
405  200 CONTINUE
407  S=S*P
410  PRINT 9, P,S,T(J)
420  9 FORMAT(3E15.8)
430  10 CONTINUE
440  PRINT: "SYSTEM RELIABILITY"
450  PRINT 8,S
460  8 FORMAT(E15.8)
470  STOP
480  END

```

Figure B-2. PREDICTION PROGRAM